VARIABLES INFLUENCING RISK SENSITIVITY IN ADULT HUMANS

By

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Three experiments examined risky choice in adult humans with procedures similar to those used to study risky choice in nonhumans. These experiments were designed both to investigate the generality of risky choice shown in previous research with humans, and to determine whether some of the discrepancies that exist between risky choice in humans and nonhumans are due to species differences or to methodological differences in how risky choice is typically assessed. In all experiments, subjects were given extensive exposure to contingencies and outcomes were real money. In Experiments 1 and 2, the choice outcomes were fixed and variable reinforcer amounts, and fixed and variable reinforcer delays, respectively. The form of the variable distribution was manipulated across conditions to determine how distributional characteristics influenced choice. In both experiments, choice was unaffected by the form of the variable distribution. Consistent with previous research with humans, choice was predominantly risk averse in Experiment 1 and risk averse or risk neutral in Experiment 2. In Experiment 3, risky choice was examined under

conditions designed to model energy-budget manipulations conducted by behavioral ecologists with nonhumans. Subjects were presented with repeated choices between fixed and variable point amounts. Positive and negative energy-budgets were simulated by manipulating the number of points that had to be accumulated within a block of trials for points to be exchanged for money. The results were generally consistent with previous energy-budget research and with the predictions of an optimal foraging model known as the energy-budget rule: Choice was risk averse when energy budgets were positive and usually risk prone when energy budgets were negative. Local choice patterns were also generally consistent with the predictions of a dynamic optimization model. The results of Experiment 3 thus demonstrated the generality of energy-budget effects, and suggested that risky choice in humans may be similar to that shown in nonhumans when choice is assessed under comparable experimental conditions. The contributions of procedural differences to discrepancies in risky choice shown across species, and the benefits of developing laboratory procedures that can be used by researchers from a variety of scientific disciplines are discussed.

INTRODUCTION

Humans and other animals are often confronted with choices that have uncertain or variable outcomes. For example, an animal might be faced with a choice between foraging in a patch that consistently yields a moderate quantity of food or foraging in a patch that yields either a high or low quantity of food probabilistically. A gambler might be faced with a choice between a bet with high odds and a small payoff, and a bet with low odds and a large payoff.

The term risk has been used to refer to environmental variability. Preference for fixed (i.e., constant) and variable alternatives has been described as risk sensitivity (Kacelnik & Bateson, 1996). (This definition of risk is to be distinguished from definitions that refer to choice between options with potentially harmful consequences). Risk sensitivity may take one of three forms. If a fixed option is preferred to a variable option, behavior is said to be risk averse. If a variable option is preferred to a fixed option, behavior is said to be risk prone (Stephens & Krebs, 1986). Finally, if no strong preference for either option occurs, behavior is said to be risk neutral or indifferent.

Risky choice in humans and nonhumans has been investigated by researchers from a variety of scientific disciplines including economics, psychology, anthropology, and behavioral ecology. This research has generally shown that behavior is sensitive to environmental variability. An overview of this research reveals, however, an apparent discrepancy between human and nonhuman risk sensitivity. Specifically, humans tend to show greater risk aversion than do nonhumans.

It is difficult to relate patterns of risk sensitivity shown in humans and nonhumans, however, because the procedures used to assess choice vary substantially from one another. Some

of these procedural differences (discussed in more detail below) include the method of presenting choice options (i.e., presented verbally or actually experienced), the number of trials over which choice is assessed (repeated choices or one-shot choice), the nature of the choice outcome (real or hypothetical), the form of the variable distribution (e.g., exponential or bivalued), and the dimension that is variable (amount or delay). The extent to which these procedural variables influence risky choice or contribute to human and nonhuman differences in risk sensitivity is unclear. Therefore, one aim of the present research was to investigate choice in humans under conditions more comparable to those used with nonhumans.

Although the factors responsible for the different patterns of risk sensitivity shown in research with nonhumans have not been precisely identified, behavioral ecologists have shown that risk sensitivity in many species varies reliably with changes in the organism's energy budget. Energy budget refers to the energy status of an organism in relation to its energy requirements (Bateson & Kacelnik, 1998). In certain species, individuals must accumulate sufficient energy reserves while foraging to survive a period in which foraging is impossible (e.g., overnight). If reserves are high or the mean rate of food intake is sufficient to exceed the energy requirement, the energy budget is positive. If reserves are low or the mean rate of food intake is insufficient to meet the energy requirement, the energy budget is negative. A number of studies conducted by behavioral ecologists (reviewed below) have shown that risk sensitivity varies as a function of energy budget (e.g., Caraco, 1983; Caraco, Martindale & Whittam, 1980). These studies have shown that choice is risk averse when the energy budget is positive and risk prone when the energy budget is negative.

Although the investigation of energy-budget effects has become one of the most promising approaches to the analysis of risky choice in behavioral ecology (see Bateson & Kacelnik, 1998; Kacelnik & Bateson, 1996), no studies have explicitly investigated energy-budget effects in

humans. It is possible that risky choice in humans may show the same shifts from risk aversion to risk seeking as nonhumans when energy budgets are manipulated.

One of the main obstacles to studying energy-budget effects in humans is the problem of manipulating food intake. The effects of negative energy-budgets are normally studied by restricting food access and presenting food reinforcers during experimental sessions at a rate that is insufficient to meet energy requirements. Even if human participants agreed to restrict food intake and deprivation levels could be verified, deprivation levels would necessarily be far above those required to induce negative-energy budgets. It may be possible, however, to create experimental procedures that model important features of energy-budget experiments without using food and/or life-death choices. That is, it may be possible to use a monetary earnings requirement in place of an energy requirement. The reinforcement contingencies established by the relationship between choice payoffs, accumulated earnings, and the earnings requirement (an "earnings" budget) could then be manipulated to simulate positive and negative energy budgets. Thus, a second aim of the present research was to develop a procedure to assess risk sensitivity in humans across manipulations analogous to energy-budget manipulations conducted with nonhumans.

Three experiments were conducted. The first two experiments investigated whether the results of previous risky-choice experiments with humans would generalize to situations that are more similar to those used with nonhumans. Specifically, human subjects were given repeated choices between fixed and variable reinforcer amounts (Experiment 1) and fixed and variable reinforcer delays (Experiment 2) across several variable distribution types. The choice outcomes were real money. These experiments were designed to examine whether some of the differences in risky choice between humans and nonhumans are due to species differences or due to methodological differences in how risky choice is assessed. The third experiment investigated choice in humans across procedural manipulations designed to model energy-budget manipulations conducted with nonhumans. This experiment was designed to examine whether shifts in risk

sensitivity shown in nonhumans across changes in energy budget would also occur in humans. The results of these experiments may contribute to the analysis of human risky choice in the laboratory and in the field, and may help assess the generality of patterns of risky choice across species. Furthermore, because the experiments combined methods and procedures from several different research areas, they may contribute to the further development of interdisciplinary risky-choice research.

EXPERIMENT 1

FIXED AND VARIABLE REINFORCER AMOUNTS

Overview

Many experiments have investigated risk sensitivity by presenting subjects with choices between a fixed reinforcer amount that is delivered with certainty and a variable reinforcer amount that is composed of a probability distribution of different amount values, one of which could be zero. For example, a risky-choice experiment with nonhumans may present subjects with choices between a fixed option that delivers 8 food pellets and a variable option that delivers 0 or 16 food pellets with equal probability (Hamm & Shettleworth, 1987). Alternatively, an experiment may present subjects with choices between a fixed option that produces 3-s access to food with certainty and variable option that produces either 1-s access to food with $p=.75$ or 9-s access to food with $p=.25$ (Staddon & Innis, 1966). Choice may be described as risk averse if the fixed amount is preferred and risk prone if the variable amount is preferred.

The results of risky-choice experiments with nonhumans using fixed and variable reinforcer amounts have shown all types of risk sensitivity. Experiments have shown that choice is risk neutral (Staddon & Innis, 1966), risk prone (Essock & Reese, 1974; Leventhal, Morrell, Morgan, & Perkins, 1959; Young, 1981), and often risk averse (Clements, 1990; Hamm & Shettleworth, 1987; Logan, 1965; Menlove, Inden, & Madden, 1979; Reboreda & Kacelnik, 1991; see Kacelnik & Bateson, 1996, for a review). For example, Essock and Reese (1974) investigated choice in food-deprived pigeons by presenting subjects with choices between fixed and variable durations of food-access time having the same mean value. Choice of four of five subjects

was risk prone across conditions. In a similar study, Hamm and Shettleworth (1987) presented food-deprived pigeons with choices between fixed and variable numbers of food pellets when both options had the same mean value. Choice of all subjects was risk averse.

In typical risky-choice experiments with humans, subjects are presented with choices between certain and variable (usually hypothetical) amounts of money. Although these experiments have also shown all types of risk sensitivity, the predominant finding is that choice is risk averse, at least when choice outcomes are gains (e.g., Kahneman & Tversky, 1979; Kohn, Kohn, & Staddon, 1992; Schmitt & Whitmeyer, 1990; Schneider, 1992; Schneider & Lopes, 1986; Silberberg, Murray, Christensen, & Asano, 1988; Tversky & Kahneman, 1992).

For example, Kahneman and Tversky (1979) reported that when 95 subjects were presented with the following choice between options delivering a hypothetical amount of money:

A: (1,000, p=.50) or B: (500)

84% of subjects preferred option B, the certain option. Similarly, Schneider and Lopes (1986) presented 1,382 college undergraduates with five choices between certain and probabilistic hypothetical amounts of money in a brief questionnaire. They reported that certain option was preferred in the majority of cases.

Although risky choice in humans appears to be more consistently risk averse than choice in nonhumans, there are many procedural differences between experiments conducted with humans and nonhumans that make comparing results difficult. Some of the more important differences are described below. In the present experiment, an attempt was made to minimize these procedural differences both to further investigate choice in humans and to provide a better comparison of human and nonhuman risky choice.

Verbal Descriptions of Contingencies versus Exposure to Contingencies

In studies with nonhumans, the probabilities of receiving each reinforcer amount are actually experienced by subjects during experimental sessions. Often, subjects are exposed to choice outcomes in forced-choice trials before the actual choice trials begin. In most studies with humans, on the other hand, the probabilities of receiving each amount are described verbally (e.g., Hershey & Schoemaker, 1980; Tversky & Kahneman, 1992). For example, a variable amount used in a choice problem by Tversky and Kahneman (1981) was presented as the verbal statement: "80% chance to win $45."

No studies have directly compared risky choice across situations in which amount probabilities are described verbally or actually experienced, although a few studies have delivered reinforcers probabilistically during experimental sessions. For example, Kohn et al. (1992) presented groups of college undergraduates with repeated choices between fixed and variable reinforcer amounts, reinforcer delays, and rates of reinforcement, using a simple computer game. Subjects participated for one session and the reinforcer for each choice was the appearance of symbols on a computer screen. In the amount conditions, choice outcomes were fixed and variable numbers of symbols. The variable option had a bivalued distribution. In one experiment, the amount of the certain option was manipulated across groups and was either equal to, greater than, or less than the mean value of the variable option. For all three groups, choice was moderately risk averse.

Schmitt and Whitmeyer (1990) investigated choice in five humans when outcomes were points exchangeable for money. One option delivered a constant number of points and the second option delivered or removed points with an equal probability. Subjects were exposed to a minimum of 12, 50-min sessions. Three subjects showed risk aversion, one showed indifference,

and one showed risk seeking. Choice of four of the five subjects became more risk averse across the experiment.

Finally, in a recent study by Lane and Cherek (1999), 12 subjects were presented with repeated choices between options delivering a small amount of money delivered with certainty or a high probability, and larger amount of money delivered with a low probability. When both options had approximately equal expected values (calculated as the amount multiplied by its probability), choice was risk averse.

Overall, these findings suggest that risk aversion may be common, both when probabilities are verbally presented, and when they are actually experienced. Because choice is maintained by different types of contingencies in these two cases, however, it is likely that the choice patterns are not entirely equivalent. That is, in the first case, choices are influenced by past experiences with stated probabilities, but in the second case, choices are influenced by contingencies arranged during the experimental setting. That patterns of risky choice maintained by these different contingencies may not be equivalent is suggested by the results of the study by Schmitt and Whitmeyer (1990), described above. In their study, risk sensitivity changed across sessions, indicating that preferences changed with continued exposure to choice outcomes.

The use of verbal descriptions of contingencies versus actual exposure to contingencies (as well as the use of one-shot versus repeated choices, described below), relates to a general criticism concerning human operant research made by Baron, Perone, and Galizio (1991). Most studies with humans examine behavior across very short periods of time whereas studies with nonhumans examine behavior until performance reaches a steady state. It is difficult to directly compare performance of humans and nonhumans when human behavior has not reached stability because early in an experimental condition behavior may be controlled by variables other than the current reinforcement contingencies.

Because the primary purpose of the present research was to study choice in humans under conditions that resemble those used with nonhumans, the present experiment arranged for subjects to experience the actual choice outcomes (rather than merely describing them) and provided subjects with extensive exposure to the contingencies. Furthermore, conditions remained in effect until performance reached a steady state.

Repeated versus One-Shot Choices

Another procedural difference between research conducted with humans and nonhumans concerns the amount of exposure to each choice outcome. Most experiments with humans present each choice once or a few times only whereas most experiments with nonhumans present the same choices repeatedly. Several studies with humans, however, have found differences in risk sensitivity when choice is compared across one-shot (unique) conditions, in which a gamble (i.e., probability distribution) is presented or played only once, and repeated conditions, in which a gamble is presented or played multiple times. For example, Keren and Wagenaar (1987) presented subjects with choices between pairs of identical gambles in both unique and repeated conditions. Subjects were instructed that the selected gamble would be played once in the unique conditions and ten times in the repeated conditions. During unique conditions, the certain outcome was preferred to a risky outcome despite having a lower expected value, but during the repeated conditions, the gamble with the higher expected value was preferred

Schmitt and Whitmeyer (1990) found opposite effects of presenting repeated versus one-shot choices. At the end of their experiment, subjects were presented with a one-shot choice between the certain and variable option. In nearly every case, choice was risk prone during the one-shot condition whereas choice was primarily indifferent or risk averse during the experiment when choices were presented repeatedly.

Although the results of Schmitt and Whitmeyer (1990) experiment conflict with those of Keren and Wagenaar (1987), these experiments show that presenting choices under unique or repeated conditions can produce different patterns of risk sensitivity. In the present experiment, to remain consistent with the procedures used to study choice in nonhumans, subjects were presented with repeated choices.

Nature of the Consequence

In all risky-choice studies with nonhumans, choices produced real outcomes. In most risky-choice studies with humans, on the other hand, choices produced hypothetical outcomes, usually hypothetical monetary amounts (e.g. Currim & Sarin, 1989; Hershey & Shoemaker, 1980; Kahneman & Tversky, 1979; Tversky & Kahneman, 1992). When hypothetical outcomes are used, it is usually assumed that choices are similar to those that would occur if real outcomes had been used (e.g., Kahneman & Tversky, 1979). Several studies with humans, however, have explicitly compared risky choice when outcomes were real or hypothetical, and have shown that choice sometimes varied with the nature of the consequence. When choice outcomes were real, choice has been shown to be more risk averse (Christensen, Parker, Silberberg, & Hursh, 1998; Lafferty & Higbee, 1974; Slovic, 1969), less risk averse (Levin, Chapman, & Johnson, 1988), or generally similar to choice when outcomes were hypothetical (Irwin, McClelland, & Schulze, 1992; Wiseman & Levin, 1996). To minimize the procedural differences from studies with nonhumans, the present experiment used real monetary outcomes.

It should also be noted that previous studies using real monetary outcomes differed in an important way from studies with nonhumans. In previous experiments with humans using real outcomes, with very few exceptions (e.g. Lane & Cherek, 1999; Schmitt & Whitmeyer, 1990), subjects did not actually experience the outcomes of choices until the end of the experiment. That

is, gambles were not played until all choices had been made. Thus, there was no opportunity for consequences to influence choice. In studies with nonhumans, on the other hand, consequences are delivered repeatedly throughout the experiment. To better approximate the procedures used with nonhumans, in the present experiment points exchangeable for money were delivered immediately following each reinforced response.

Form of the Variable Distribution

Risky-choice experiments with humans and nonhumans also differ in the types of variable distributions that are typically used to assess choice. Experiments with humans have most often used two-outcome (bivalued) probability distributions, but experiments with nonhumans have investigated choice across a much wider range of distribution forms. Furthermore, several studies with nonhumans have shown that the form of the variable distribution, including its minimum value, variance, and skew, can influence preference.

For example, Essock and Reese (1974) showed that when pigeons were presented with choices between fixed and variable food-access times, choice was risk prone across several different distribution forms, but choice was most risk prone during conditions in which the variable distribution had a high minimum value.

Caraco and Lima (1995) presented three, dark-eyed juncos with choices between a certain and a variable number of seeds. They reported that when the certain option was pitted against one of several variable distributions, each of which had the same mean value but different standard deviations, preference for the certain option increased as the standard deviation of the variable option increased. These results were described in terms of a "trade-off" between mean and variance. Similar results have been shown in another bird species, bananaquits (Wunderle & Cotto-Navarro, 1988). Furthermore, when Caraco and Chasin (1984) presented three, white-

crowned sparrows with choices between two variable distributions having the same mean value but different skews, the positively skewed distribution (mode > median > mean) was preferred to the negatively skewed distribution (mean < median < mode).

One psychological model that predicts that risky choice may be influenced by the shape of the variable amount distribution is scalar expectancy theory, or SET (Gibbon, 1977). SET was originally proposed as a model of temporal discrimination but has been extended to choice between fixed and variable reinforcer delays by Gibbon, Church, Fairhurst, and Kacelnik (1988). Predictions of SET have also been extended to choice between fixed and variable reinforcer amounts when amounts are programmed as fixed and variable durations of food access (Reboreda & Kacelnik, 1991). According to Gibbon et al., SET predicts that a variable option having a bivalued, rectangular, or positively skewed (exponential) distribution of delays will be preferred to a fixed-delay option having the same mean value. When the distribution of the variable option is negatively skewed (reverse exponential), however, the fixed and variable option may be equally preferred. Gibbon et al. presented data from a study with pigeons consistent with these predictions.

One of the few studies with humans examining the effects on choice of the form of the variable distribution was conducted by Lopes (1984). Subjects were presented with choices between pairs of lotteries, or a certain outcome and a lottery having the same mean value (hypothetical $100). A variety of distributions was used including normal, rectangular, bivalued, and skewed. Lopes ranked each distribution according to a measure of variability called the lottery's <u>inequality</u>. Distributions were presented as bar graphs. Subjects were classified according to their preferences between certain and variable gambles. Overall, choice in 46% of subjects was risk-averse, choice in 34% of the subjects was indifferent, and choice in 20% of the subjects was risk prone. For subjects whose choices were risk averse, preference for a lottery decreased as its inequality increased, with lotteries having the lowest inequality being most strongly

preferred (i.e., gambles with a negative skew and a low probability of receiving $0). For subjects whose choices were risk prone, the opposite pattern was observed. In a second study, subjects were also presented with choices between positively and negatively skewed distributions with equal standard deviations. The minimum value of the negatively skewed distribution was $0 but the minimum value of the positively skewed distribution was above $0. For subjects whose choices were risk averse, the positively skewed distribution was preferred.

Lopes' (1984) research shows that choice of humans, like choice of nonhumans, is sensitive to distributional characteristics. The procedures used by Lopes, however, were very different from those used in studies with nonhumans: Subjects were given few choice trials and amount probabilities were described verbally (i.e., in graph form) rather than being actually delivered.

The present study sought to investigate further the effects on risky choice of the form of the variable distribution by presenting subjects with repeated choices between fixed and variable amounts when the amount probability distributions were actually experienced.

Specific Rationale for Experiment 1

The many procedural differences between risky-choice experiments with humans and nonhumans make comparing patterns of risk sensitivity difficult. Thus, the aim of Experiment 1 was to determine whether patterns of risk sensitivity shown in humans during typical risky-choice experiments would generalize to choice contexts that more closely approximate those used with nonhumans.

As mentioned previously, one notable procedural difference between experiments with humans and nonhumans is that experiments with nonhumans arrange for subjects to experience choice contingencies whereas most studies with humans only present subjects with verbal

descriptions of choice contingencies. The present experiment attempted to control for these differences by arranging for human subjects to experience choice outcomes directly. This was accomplished in two ways. First, the different reinforcer amounts were actually delivered during experimental sessions according to their programmed probabilities. For example, when the variable distribution was bivalued, the variable option added either 25 or 75 points with equal probability to a counter and the fixed option always added 50 points to the counter. Second, half of the trials of each session were forced-choice trials to guarantee exposure to both the fixed and variable outcomes before the choice trials were presented.

A second procedural difference concerns the degree of exposure to contingencies. Experiments with nonhumans present subjects with repeated choices between fixed and variable amounts but typical experiments with humans present subjects with few choices. Thus, in the present experiment subjects were given long-term exposure to choice contingencies. Specifically, each experimental session consisted of 30 choice trials and conditions were in effect for a minimum of six sessions and until performance stabilized. The total number of sessions each subject experienced ranged from 43 to 74.

Third, choice outcomes in risky-choice experiments with nonhumans are nearly always real, whereas choice outcomes in experiments with humans are most often hypothetical. To more closely approximate the procedures used with nonhumans, the present experiment used points exchangeable for real money as consequences.

Finally, experiments with humans have investigated choice across a variety of different distribution forms, but most experiments with humans have used only bivalued distributions. In the present experiment, choice was assessed across four different probability distributions. The form of each distribution, shown in Figure 1, was either bivalued, rectangular, (approximately) normal, or reverse exponential (negatively skewed). Also shown in Figure 1 is the standard

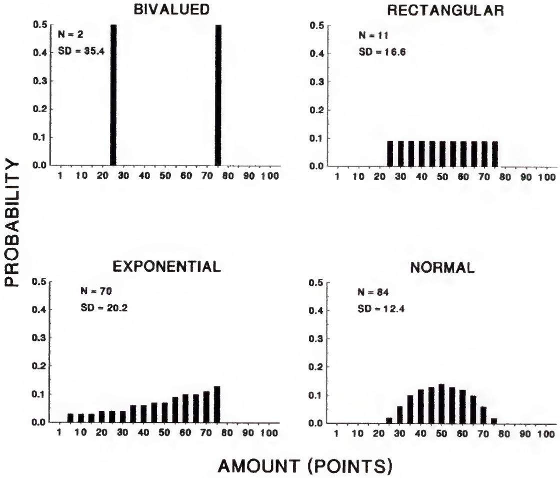

Fig. 1. Probability distributions used in Experiment 1. SD indicates the standard deviation and N indicates the number of elements in each distribution.

deviation and number of elements in each distribution. All distributions had the same mean value and, with the exception of the exponential distribution, the same minimum value. If choice of humans is consistent with predictions of choice models such as SET, then choice would be more risk averse when the certain option was paired with the bivalued, rectangular, or normal distributions, than when paired with the reverse-exponential distribution. If risky choice is influenced by the degree of variability, then choice may be more risk averse when the variable distribution has a high standard deviation (i.e., when the distribution is bivalued) than when it has a low standard deviation (i.e., when the distribution is approximately normal).

Method

Subjects

The subjects were three adult humans recruited via an advertisement in a local university newspaper. Subject 211 was a 20 year-old male and Subjects 212 and 218 were 19 and 20 year-old females, respectively. None had any previous experience with behavioral research. At the termination of the experiment, subjects were mailed a check for money earned during each experimental session (approximately $3.00 per session) plus $1.50 for each completed session. Overall, subjects earned approximately $6.00 per hour.

Apparatus

Subjects were seated in a cubicle measuring 2.21 m high, 1.21 m wide, and 1.25 m deep, facing a white, aluminum panel 74 cm high and 44.5 cm wide. The upper portion of the panel contained 3 rows of 12 bulbs, with each row spaced 8 cm apart. The first and last bulb of each row were covered with white translucent caps; the 10 inner bulbs of each row were covered with red translucent caps. Three 2.5 cm response keys, positioned 8.2 cm from one another, were mounted 8.2 cm below the lowest row at approximately eye level. A force of approximately 0.6 N was required to operate the response keys. A 4-digit 2.5 cm by 5 cm electromechanical counter was mounted 19.5 cm below the left response key. The counter was centered in an 8.8 cm by 7.7 cm opening on the aluminum panel covered with Plexiglas. An overhead light provided diffuse illumination and a ventilation fan helped mask extraneous sound.

Several changes were made to the apparatus before Subject 218 began the experiment. First, the lower section (23.5 cm) of the aluminum panel was removed and replaced with a white, wooden panel. A 20 cm by 15 cm opening for a television monitor (not used in the present experiment) was positioned 4 cm from the left side of the panel and 9.8 cm below the response

keys. A predetermining counter (not used in the present experiment) was mounted 7 cm to the right of the monitor. The 4 digit electromechanical counter was re-positioned beneath the right key, 3 cm to the right of the predetermining counter and 15 cm above the bottom of the panel. Both counters were mounted directly on the wooden panel.

Procedure

Each session consisted of 60 trials (30 forced-choice trials and then 30 choice trials) in which choices could produce either a fixed or variable number of points. During choice trials, the left and right keys were illuminated and flashed according to a 0.25 s on-off cycle. The fixed and variable alternatives were correlated with yellow and green keylights, respectively. The side position of the fixed and variable alternative was randomly determined each trial. During the choice period, five consecutive responses on one of the keys stopped the keylight from flashing (the keylight became continuously illuminated), disabled the alternative schedule, and initiated a 10-s delay. The first response after 10 s had elapsed darkened the response key and, depending on the schedule type, produced a fixed number of points (50) or a variable number of points (averaging 50). During the delay period, a 5-s delay was programmed between responses on dark keys and point presentations. For Subjects 211 and 212, during a pre-training period lasting 16 and 5 sessions, respectively, only a single response was required during the choice period and one additional response was required to produce points.

Forced-choice trials were similar to choice trials except that only one side key was illuminated. The schedule type (fixed or variable) was randomly determined each trial with the following restrictions: (a) Neither schedule type could occur consecutively on more than three trials, and (b) each schedule type occurred on half of the trials. To hold the rate of trial onset constant, trials were presented every 45 s. Because the time required to deliver points varied with the point amount, the actual inter-trial interval (ITI) could vary from trial to trial.

Prior to the first experimental session, the following instructions were presented and read to each subject:

> Every 10 points displayed on the counter is worth $0.01. For example, if the counter shows 500 points you have earned $0.50. You can earn points by pressing the response keys when lit. Please remain seated. You will be informed when the session is over.

Choice was assessed across four distribution types: bivalued, (approximately) normal, reverse exponential, and rectangular. Table 1 shows the sequence and number of sessions per condition for each subject. The order of exposure to each distribution varied across subjects and in most cases each distribution was presented twice. Conditions were changed after a minimum of six sessions and when the number of choices for the fixed option was stable across a five-session block, as determined by visual inspection. Sessions were conducted at approximately the same hour, Monday through Friday. Typically, two sessions were conducted daily and sessions were separated by a minimum of 10 min.

Table 1

Sequence and number of sessions per condition for each subject in Experiment 1.

	Subject		
Condition	211	212	218
Bivalued	2 (9)	3 (6)	4 (6)
	5 (7)	8 (11)	
Exponential	4 (6)	1 (18)	2 (12)
	7 (7)	6 (6)	5 (6)
		9 (6)	
Normal	1 (5)	2 (9)	3 (6)
	6 (8)	5 (6)	
	9 (6)		
Rectangular	3 (12)	4 (6)	1 (7)
	8 (7)	7 (6)	6 (6)

Results

Figure 2 shows the mean number of choices for the fixed option per session across the final five sessions of each condition. Filled bars show the results from the initial exposure to each distribution and open bars show the replications. Vertical lines show the standard deviations of the session values. The horizontal line indicates the indifference point between the two options. Choice was defined as risk averse if the number of choices for the fixed option was above this line, and risk prone if the number of choices was below it.

Choice was risk averse in most conditions and there was no systematic effect on choice of the form of the distribution. For Subject 211, choice was strongly risk averse during the first condition (normal distribution). Across subsequent conditions, the mean number of choices for the fixed option decreased for this subject, but remained consistently above 15 in all conditions. For Subject 212, choice was only slightly risk averse during the first condition of the experiment (exponential distribution), but was strongly risk averse during the remaining conditions. Similarly, for Subject 218 choice was slightly risk prone during the first condition (rectangular distribution) and slightly risk averse during the second condition of the experiment (exponential distribution), but was strongly risk averse during the remaining conditions.

The right and left panels of Figure 3 show for each subject the mean obtained point amounts per trial on the variable option during forced-choice and choice trials, respectively. Because differences between the first and second exposures to each distribution were generally small, results from both exposures have been combined. The vertical lines show the standard deviations of the values from both exposures. During forced-choice trials, the average number of obtained points on the variable option was very close to the value of the fixed amount (50 points) across all distribution types. During choice trials, the average number of obtained points was also near 50 in most cases but, as a result of the fewer number of variable choices, the values showed

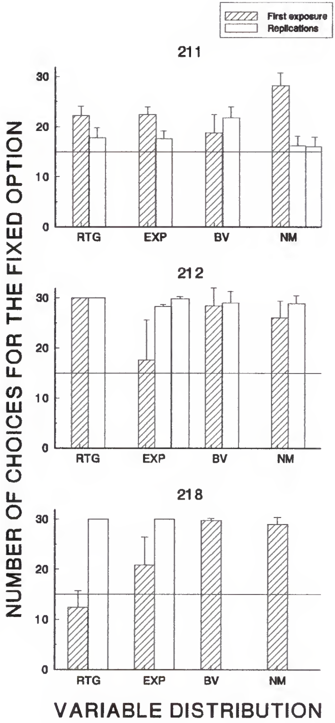

Fig. 2. Mean number of choices for the fixed option per session across the final five sessions of each exposure to the rectangular (RTG), exponential (EXP), bivalued (BV), and normal (NM) distributions for each subject in Experiment 1. The filled bars show values from the initial exposures to each condition and open bars show values from the replications. The horizontal line shows the indifference point between the two options. Vertical lines show standard deviations.

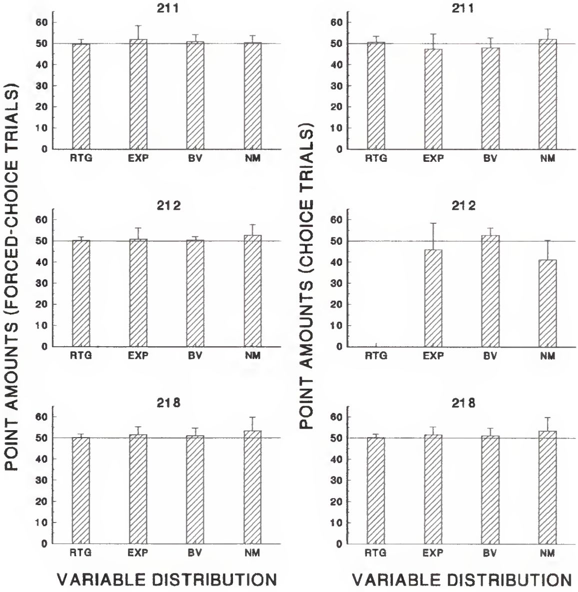

Fig. 3. Mean obtained point amounts on the variable option per trial during exposures to the rectangular (RTG), exponential (EXP), bivalued (BV), and normal (NM) distributions for each subject during forced-choice trials (left panel) and choice trials (right panel). Values from initial exposures to each condition and replications have been combined. The horizontal line shows the point amount of the fixed option per trial (50 points). Vertical lines show standard deviations.

somewhat more variability. For Subject 212, the obtained point amounts were zero during both exposures to the rectangular distribution due to an exclusive preference for the fixed option.

Discussion

When three subjects were given repeated choices between fixed and variable amounts of points exchangeable for money across a prolonged exposure to experimental contingencies, choice of all subjects was risk averse. It is unlikely that these results can be attributed to differences in average reinforcement rates between the fixed and variable options, because the obtained average point amounts were generally similar on both the fixed and variable options.

The overall pattern of risk sensitivity is thus consistent with previous research with humans using few choice trials and hypothetical amounts of money (Kahneman & Tversky, 1979; Schmitt & Whitmeyer, 1990). That choice patterns varied across initial exposures to conditions and replicated conditions suggests, however, that extensive exposure to choice outcomes may produce different patterns of risk-sensitivity than single-shot choice procedures.

In contrast to the results of previous studies with nonhumans and the predictions of several choice models, the form of the variable amount distribution had no effect on preference. For two subjects (Subjects 212 and 218), it is likely that the strong risk aversion obscured any effect that the different distribution forms may have had on choice. For example, Lopes (1984) showed that subjects who showed a preference for a fixed option over several different variable distributions showed a preference for less variable distributions over more variable distributions when both choice outcomes were variable. It is possible, therefore, that if both choice options in the present experiment were variable amounts, choice of these two subjects may have showed greater sensitivity to distributional characteristics. For Subject 211, however, choice was much less risk averse than in the other two subjects, but choice did not vary as a function of the distribution form.

Overall, the results of the present experiment suggest that the patterns of risk-sensitivity shown in previous studies with humans generalize to situations that are more similar to those used to study choice in nonhumans. These results also suggest that some of the procedural differences between experiments with humans and nonhumans, including the presentation of probabilities, repeated versus one-shot choices, real versus hypothetical outcomes, and the form of the variable distribution, cannot account for the more frequent reports of risk seeking in studies with nonhumans than in studies with humans.

EXPERIMENT 2

FIXED AND VARIABLE DELAYS TO REINFORCEMENT

Overview

Analyses of risky choice have traditionally focused on preferences between fixed and variable reinforcer amounts, but amount is only one dimension along which variability can occur. Variability may also occur in the delay to reinforcement. Experiments investigating choice between fixed and variable delayed reinforcers have not usually been conceptualized in terms of risk, most likely because the variables controlling preferences for amounts and delays are assumed to be different (but see Rachlin, Logue, Gibbon & Frankel, 1986; Reboreda & Kacelnik, 1991). In both cases, however, choice in humans and nonhumans has been shown to be sensitive to variability (i.e., risk sensitive).

In choice experiments using delays, subjects are typically presented with choices between a fixed option, in which the reinforcer delay is constant, and a variable option, in which different reinforcer delays occur probabilistically. Preference for the fixed-delay option may be described as risk averse, and preference for the variable-delay option may be described as risk prone.

Although choice in nonhumans appears to be less consistently risk averse than choice in humans when outcomes are amounts, differences in risk sensitivity between nonhumans and humans appear to be much more extreme when outcomes are delays. Experiments with nonhumans have repeatedly shown that choice for reinforcer delays is strongly risk prone (Bateson & Kacelnik, 1995; Cicerone, 1976; Davison, 1969, 1972; Frankel & Vom Saal, 1976; Herrnstein, 1964; Killeen, 1968; Mazur, 1984; Pubols, 1962). Nonhumans have also shown a preference for

variable-ratio (VR) over fixed-ratio (FR) schedules of reinforcement, and this finding is usually interpreted in terms of a preference for variable delays to reinforcement (Fantino, 1967; Rider, 1983; Sherman & Thomas, 1968). To the author's knowledge, however, only two studies have investigated risky choice in humans with fixed and variable reinforcer delays, and the results of both of these studies were inconsistent with results of studies with nonhumans.

Weiner (1966) investigated choice in humans between two ratio schedules of point delivery. In one condition, the two schedules were a FR 40 and a VR 40 schedule. The elements of the variable schedule varied randomly from 1 to 80. Weiner found no strong preference for either schedule. These results are inconsistent with previous research with nonhumans that has shown that VR schedules are highly preferred to FR schedules of the same mean value (e.g., Fantino, 1967).

In some conditions of a study described earlier, Kohn et al. (1992) presented subjects with repeated choices between fixed and variable delays to the presentation of symbols on a computer screen. A sequence of four experiments was conducted. The delay schedules were fixed-time (FT) and variable-time (VT) schedules in which symbols were delivered after fixed and variable delays from the choice; no additional response was required to produce symbols once the delay timed out. In two experiments, the variable option was a VT 5-s schedule composed of two intervals, 1 s and 9 s ($p=.5$). Across groups of subjects, the FT schedule either equaled, was greater, or was lower than the arithmetic mean of the VT schedule. Choice was risk prone when the FT schedule value was greater than the mean value of the VT schedule, but was risk averse when the FT schedule value was equal to or greater than the mean value of the VT schedule. In another experiment, the intervals of the VT schedule were either 1 and 19 s (Long-delay group) or 1 and 3 s (Short-delay group). The value of the FT schedule equaled the mean value of the VT schedule. In both groups, choice was risk averse.

The results of the three experiments by Kohn et al. (1992) contrast with the results of research with nonhumans in which variable delays to reinforcement were strongly preferred to fixed delays having the same mean value (e.g. Cicerone, 1976; Pubols, 1962). In only one of their experiments was choice moderately risk prone. In that experiment, no distinct stimulus was correlated with the choice, outcome, or ITI portion of a trial.

Although risky choice in nonhumans appears quite different than risky choice in humans when outcomes are reinforcer delays, it is difficult to directly compare these results. The main problem is that there are very few studies with humans on which to base a comparison. For example, many risky choice studies with nonhumans have used VI and FI reinforcement schedules (e.g., Herrnstein, 1964; Killeen, 1968), but studies with humans have only used VR and FR and VT and FT schedules. In addition, many studies with nonhumans have shown that the form of the variable delay distribution can have large effects on risk sensitivity. No studies with humans, however, have yet investigated the effects on choice of distributional characteristics.

Form of the Variable Distribution

Most studies that have shown that risky choice is influenced by the form of the variable delay distribution were not designed to study risky choice per se. Rather, they were designed to identify the averaging principle that best characterizes the reinforcement rate or, more generally, the value of a variable reinforcement schedule. This averaging principle is then used to predict preference between pairs of reinforcement schedules with delayed outcomes. A variety of averaging principles have been proposed, but all of them assume that the reinforcing effectiveness of a choice outcome decreases as a function of its delay. That is, reinforcers that occur with a short delay are assumed to have a stronger effect on choice than reinforcers that occur with a longer delay.

Killeen (1968), for example, presented pigeons with choices between several different FI and VI reinforcement schedules to determine the FI schedule that was equally preferred to the VI schedule. He reported that the harmonic mean of the VI distribution provided a good estimate of the FI schedule value at which choice was indifferent between the two schedules. Harmonic means, unlike arithmetic means, differentially weight the short delay values of a distribution. To test this model further, Killeen presented pigeons with choices between two VI schedules. The distributions of the two schedules were constructed so that one schedule had a higher arithmetic mean but a lower harmonic mean than the other. All subjects showed a preference for the VI schedule with the lower harmonic mean.

Averaging principles comparable to the harmonic mean have also been proposed by Bateson and Kacelnik (1995, 1996) and Mazur (1994, 1996). Bateson and Kacelnik showed that an averaging principle based upon the short-term rate of reinforcement (gain per interval divided by the interval), called the expectation of ratios (EoR), provided a better description of preference than an averaging principle based upon the mean rate of reinforcement (total gain divided by total time). Similarly, Mazur showed that a hyperbolic discounting function provided a good estimate of the fixed schedule values that were equally preferred by pigeons to several different variable schedules. According to Mazur's model, the value of a variable schedule is determined by the sum of the reciprocals of each delay interval, with each delay weighted by its probability of occurrence.

All of the averaging principles described above predict that the short delays of a variable distribution are given more weight than the long delays in calculations of reinforcement rate or value. Thus, these models would predict that the relative frequency of short and long delay values in a variable distribution (i.e., the form of the variable distribution) will influence risk sensitivity.

Scalar expectancy theory, or SET, also predicts that choice should be risk prone for reinforcer delays and that the form of the variable delay distribution influences choice (Gibbon et

al., 1988). As described above, SET predicts that a variable option will be preferred to a fixed option when the variable distribution is rectangular, bivalued, or forward exponential (positively skewed). Choice should be risk neutral, however, when the variable distribution has high proportion of long delay elements, such as when the distribution is reverse exponential (negatively skewed). Support for these predictions was provided by two experiments with pigeons using VI schedules with forward-exponential and reverse-exponential distributions (Gibbon et al., 1988). These experiments showed that the VI schedule was preferred to a constant-delay option when the form of the variable distribution was forward exponential, but that the VI schedule was equally preferred to the constant-delay option when form of the distribution was reverse exponential.

Two other distributional characteristics that have been investigated with nonhumans are the number of delay intervals and the value of the smallest delay interval in the variable distribution. For example, Davison (1972) presented pigeons with choices between FI and VI reinforcement schedules with the same mean value. Across conditions, the number of intervals in the VI schedule was manipulated while the minimum (and maximum) interval was held constant. Davison showed that preference remained constant across all conditions.

Results of several studies have suggested that the smallest value of a variable schedule influences choice (Ahearn & Hineline, 1992; Cicerone, 1976; Duncan & Fantino, 1970; Fantino, 1967). Ahearn and Hineline, for example, presented pigeons with choices between mixed-ratio (MR) schedules composed of two ratio values and FR schedules having the same or lower arithmetic mean value. The results showed that a MR 60.5 schedule composed of ratio values of 1 and 120 was preferred to a FR 15 schedule, but that the FR 15 schedule was preferred to a MR 60.5 schedule composed or ratio values of 15 and 105. In a similar study, Fantino (1967) showed that preference of pigeons for MR 50 schedules paired with FR 50 schedules increased as the lowest value of the MR schedule increased from 1 to 25.

These studies show that distributional characteristics, including the form of the variable distribution and the minimum value of a variable distribution, can have large effects on risky choice for delayed outcomes in nonhumans. The effects of distributional characteristics on risky choice in humans, however, have not been studied directly. In both the Weiner (1966) and the Kohn et al. (1996) experiments, only one variable distribution was used (rectangular and bivalued, respectively). Thus, a primary goal of the present experiment was to investigate risky-choice in humans across several different variable distributions. These manipulations would not only determine whether choice of humans is influenced by distributional characteristics, but would also provide a better basis for comparing risky choice in humans and nonhumans for delayed outcomes.

Probability Discounting of Monetary Reinforcers

One interpretation of the risk indifference and risk aversion shown in the experiments by Weiner (1966) and Kohn et al. (1996) is that the reinforcers (points and symbol presentations) were not discounted by their delay. Research with probabilistic monetary reinforcers has suggested, however, that choice of humans does indeed show delay discounting.

Rachlin et al. (1986) proposed that probabilistic reinforcers are functionally equivalent to fixed reinforcers that are delayed. Probabilistic reinforcers are similar to delayed reinforcers because they are delivered after a variable number of choices. For example, if choice trials are separated by 60-s ITIs, a reinforcer that occurs with $p=.25$ will occur on average after a 180 s delay (i.e., after 3 ITIs). Delay discounting can thus explain risk aversion for certain and probabilistic reinforcer amounts. That is, because probabilistic reinforcers are discounted, when subjects are presented with choices between certain and probabilistic reinforcers, the certain reinforcer is preferred. (It should be noted that this interpretation of risk aversion applies only for amount distributions with no-gain or zero amount values).

Results of a number of experiments with humans (Rachlin, Castrogiovanni, & Cross, 1987; Rachlin et al. 1986; Rachlin, Raineri, & Cross, 1991; Rachlin & Siegel, 1994) and nonhumans (King, Logue, & Gleiser, 1992; Mazur, 1989, 1991; Mazur & Romano, 1992) have generally supported this assumption (but see Christensen et al., 1998; Green, Myerson, & Ostaszewski, 1999 for one inconsistency between delay and probability discounting). These studies thus suggest that when outcomes are monetary reinforcers, choice of humans, like choice of nonhumans, may show delay discounting.

Specific Rationale for Experiment 2

A substantial amount of research with nonhumans has shown that variable delays to reinforcement are strongly preferred to fixed delays, yet very few studies have been conducted with humans. This difference may account for the more frequent reports of risk proneness in risky-choice experiments with nonhumans. Thus, the present research sought to investigate further risky choice in humans with delayed reinforcers. Specifically, subjects were presented with repeated choices between FI and VI schedules of reinforcement with approximately equal arithmetic mean values (30 s). Although risky choice in nonhumans has been frequently assessed with FI and VI schedules, no experiments have investigated risky choice in humans with these schedule types. The mean value of the FI and VI schedules was selected to approximate the schedule values used in previous risky-choice experiments with nonhumans (e.g. Bateson & Kacelnik, 1995; Davison, 1969; Killeen, 1968).

Although risky-choice studies with nonhumans have suggested that the form of the variable delay distribution can be an important determinant of risk sensitivity, the effects of distributional characteristics on human risky choice have not been systematically investigated. Thus, in the

present experiment, choice was assessed across bivalued, rectangular, normal, and exponential (positively skewed) distributions. Each distributions is plotted in Figure 4. Included on each plot is the arithmetic mean, harmonic mean, and number of delay intervals in the distribution. If choice is consistent with previous research with nonhumans, then preference for the VI schedule should increase as the harmonic mean decreases. To investigate the effects of the form of the variable distribution apart from the minimum delay value, all distributions had the same minimum value of 1 s.

One difference between the risky-choice experiments with delayed outcomes conducted with nonhumans and the two studies with humans (Kohn et al., 1996; Weiner, 1966) is the nature of the reinforcer. In risky-choice studies with nonhumans, choices produced powerful consequences, normally food. In the Weiner experiment choice outcomes were points and in the Kohn et al. (1996) experiments choice outcomes were the appearance of symbols on the computer screen. These reinforcers were probably much weaker reinforcers than the food deliveries used in the experiments with nonhumans.

Because differences in the nature of the outcome may contribute to the differences in risk sensitivity in humans and nonhumans, the present experiment used a presumed more potent reinforcer, real money. Although the Weiner (1966) and Kohn et al. (1996) experiments suggest that humans do not show delay discounting for points or symbols, the results of studies using probabilistic reinforcers suggest that delay discounting may occur for monetary reinforcers. Thus, by using real money, risky choice in humans may be more consistent with risky choice in nonhumans. All other methodological features from Experiment 1, such as extensive exposure to contingencies, steady-state analyses, etc., were also in place here.

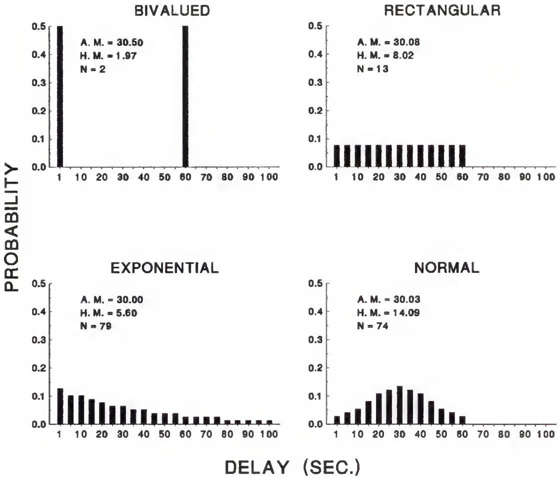

Fig. 4. Probability distributions used in Experiment 2. A.M. is the arithmetic mean, H.M. is the harmonic mean, and N is the number of elements in each distribution.

Method

Subjects

Four adult humans participated. Three subjects (Subject 203, a 25 year-old female, Subject 204, a 26 year-old male, and Subject 206, a 37 year-old male) were recruited via an advertisement in a local university newspaper. Subject 205 was female employee of the Department of Psychology and was approximately 30 years old. All subjects reported no previous experience with behavioral research. At the termination of the experiment, subjects were mailed a

check for the money earned during each session ($3.00 per session) plus $1.50 for each completed session. Total earnings thus averaged approximately $9 per hour.

Apparatus

The apparatus was the same as that used in Experiment 1, except that there were no counters and no opening for a television monitor on the panel. Instead, the lower 23.5 cm of the response panel was fitted with a solid piece of aluminum.

Procedure

Each session consisted of 60 trials. The first 30 trials of a session were forced-choice trials and the second 30 were choice trials. During choice trials, both the left and right keylights were illuminated concurrently and flashed according to a 0.25 s on-off cycle. The FI 30-s schedule was correlated with a yellow keylight and the VI 30-s schedule was correlated with a green keylight. The key position for each schedule type was randomly determined each trial. A single response stopped the keylight from flashing, extinguished the alternative keylight, and initiated the schedule timer. Completing the FI or VI schedule requirement extinguished the keylight and illuminated a single, red light. Red lights were illuminated left to right, beginning with the top row. The next trial began immediately following the light illumination. Forced-choice trials were similar to choice trials except that only one alternative was presented. The schedule type presented during forced-choice trials was determined randomly each trial, with the restriction that neither the FI or VI schedule was presented consecutively on more than three trials. Because the light panel contained only 30 red lights, the lights were extinguished following the final, forced-choice trial so that they could be re-illuminated during the choice trials.

Prior to the first experimental session, the following instructions were presented and read to each subject:

> You have already earned \$1.50. Bonus earnings may be obtained by turning on the red lights. Each time a red light is turned on, you have earned an additional 5¢. You can turn on these lights by pressing the response keys on the front panel. Please remain seated. You will be informed when the session has ended.

Across conditions, the form of the VI-schedule distribution was systematically manipulated and was either bivalued, normal, exponential, and rectangular. Table 2 shows the sequence and number of sessions per condition for each subject. The order of exposure to each distribution was randomly determined. Conditions were changed following a minimum of six sessions and when the number of FI-schedule choices was stable across a five-session block, as determined by visual inspection. Across the first five conditions, choice in Subject 205 showed no preference for either alternative but an analysis of responding revealed a stereotypic pattern of key pressing that included responding on dark keys. To eliminate this pattern, a 5-s delay was added between dark-key responses and light presentations. This manipulation was successful in disrupting the

Table 2

Sequence and number of sessions per condition for each subject in Experiment 2.

	Subject			
Condition	203	204	205	206
Bivalued	1 (11) 5 (6)	3 (25)	4 (16) 8 (13)*	2 (9) 5 (6)
Exponential	2 (22) 8 (13)	2 (31)	1 (8) 5 (24) 7 (8)*	3 (6) 8 (6)
Normal	4 (8) 7 (19)	4 (9)	2 (6) 9 (6)*	1 (7) 6 (6)
Rectangular	3 (14) 6 (6)	1 (25)	3 (6) 6 (30)*	4 (6) 7 (6)

* Conditions conducted with a 5-s delay programmed between responses on dark keys and light presentations. See text for details.

stereotypic response pattern and remained in effect during all subsequent conditions. Only results from the conditions conducted with this delay are reported. These conditions are noted with an asterisk in Table 2.

Sessions were conducted at approximately the same hour, Monday through Friday. Typically, one session was conducted daily. Several days a week, two sessions were conducted for Subjects 203 and 204. These sessions were separated by approximately 1.5 hr.

Results

Figure 5 shows for each subject the mean number of choices for the fixed option per session across the final five sessions of each condition. The horizontal line at 15 indicates the indifference point between the two options. Choice was defined as risk averse if the number of choices for the fixed option fell above this line, and risk prone if the number of choices for the fixed option fell below it. Across all subjects, the form of the variable distribution had no effect on choice. For Subject 203, choice was indifferent between the FI and VI schedules during the first condition (bivalued distribution) but was slightly risk averse across the remaining conditions of the experiment. For Subject 204, the number of FI choices was more variable than for the other subjects but showed no consistent preference for either alternative. For Subject 205, choice was also indifferent between the two schedules . For Subject 206, choice showed a near-exclusive preference for the FI schedule across all conditions.

The left and right panels in Figure 6 show mean response rates and pauses (time to the first response), respectively, on the FI and VI schedules during choice trials for each subject. Values are the mean of the final five sessions of each condition. Because results were similar across exposures in most cases, results from initial exposures and replications have been combined. The vertical lines show the standard deviation of these values. Axes are individually-scaled for each subject. Across all subjects, the form of the variable distribution had no systematic effect on

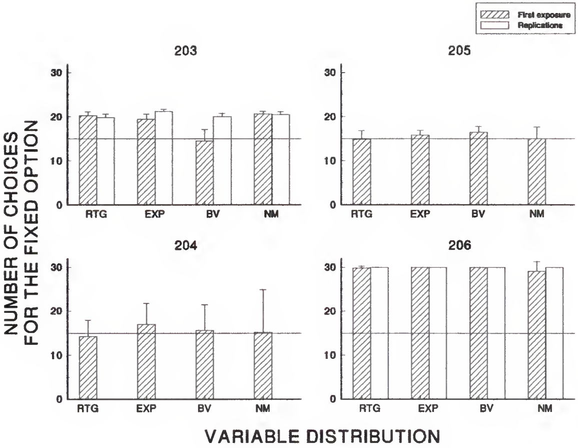

Fig. 5. Mean number of choices for the fixed option per session across the final five sessions of each exposure to the rectangular (RTG), exponential (EXP), bivalued (BV), and normal (NM) distributions for each subject in Experiment 2. The filled bars show values from the initial exposures to each condition and open bars show values from the replications. The horizontal line shows the indifference point between the two options. Vertical lines show standard deviations.

response rates or pauses. There were large differences in absolute response rates between subjects; response rates were frequently above 100 responses/min for Subject 203, usually below 10 responses/min for Subjects 204 and 205, and near 2 responses/min for Subject 206. For Subjects 203, 204, and 206, response rates were also greater on the VI than FI schedule, although for Subject 206 the VI schedule was rarely chosen. Responses rates for Subject 205 were similar on both the FI and VI schedules across conditions. Pauses tended to be slightly greater on the VI

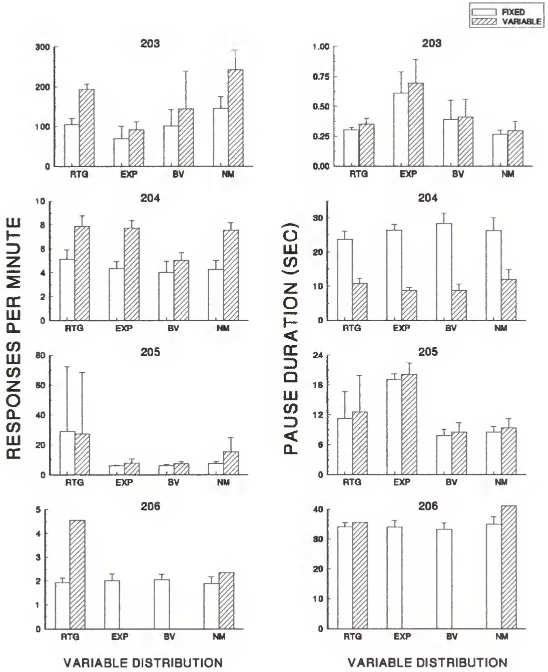

Fig. 6. Mean response rates (left panel) and pause durations (right panel) on the fixed-interval schedule (filled bars) and variable-interval schedule (open bars) across the final five sessions of the rectangular (RTG), exponential (EXP), bivalued (BV), and normal (NM) distributions for each subject. Values from initial exposures and replicated conditions have been combined. Axes have been individually scaled. Vertical lines show standard deviations.

schedule for Subjects 203, 205, and 206, but were much greater on the FI schedule for Subject 204. Subject 206 showed the longest overall pause durations, with pauses typically exceeding 30 s.

The left and right panels in Figure 7 show the mean obtained delays to light illuminations during forced-choice and choice trials for both the FI and VI schedules, averaged across the final five sessions of each condition. Results from initial exposures and replicated conditions have been combined. The vertical lines show standard deviations. For Subjects 203, 204, and 205, obtained delays were similar across distributions and across forced-choice and choice trials. Obtained delays varied between 30 and 35 s in most cases, but were slightly above 35 s for Subject 205. For Subject 206, during forced-choice trials obtained delays varied between 30 s and 40 s on the FI schedule but were consistently longer (between 40 s and 70 s) on the VI schedule. During choice trials, few variable delay values were experienced for this subject due to the strong preference for the fixed option.

Discussion

When adult humans were presented with repeated choices between FI and VI schedules having the same mean value as the form of the VI distribution was manipulated across conditions, two subjects showed a preference for the FI schedule (risk aversion) and two subjects showed no strong preference for either alternative (risk indifference). In all subjects, choice was unaffected by the form of the variable distribution. Choice patterns were thus generally similar across subjects, although there were often large individual differences in response rates and pauses. With the exception of Subject 206 (see below) these patterns of risk sensitivity cannot be explained by differences in average delays to reinforcement on the FI and VI schedule: Across forced-choice and choice trials obtained delays on both schedules were near the programmed value (30 s) in all conditions. Overall, these results are consistent with the few previous studies with humans (Kohn

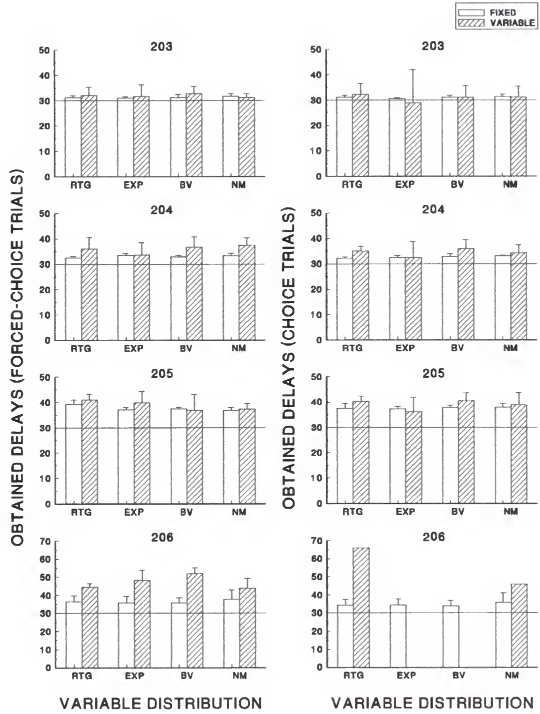

Fig. 7. Mean obtained delays to light illuminations on the variable option per trial across exposures to the rectangular (RTG), exponential (EXP), bivalued (BV), and normal (NM) distributions for each subject during forced-choice trials (left panel) and choice trials (right panel). Values from the initial exposures and replications of each condition have been combined. The vertical lines show standard deviations. The horizontal line shows the delay value of the fixed option per trial (30 s).

et al., 1996; Weiner, 1966) but are inconsistent with a large body of nonhuman research that has shown risk proneness (e.g. Herrnstein 1964; Killeen, 1968).

It could be argued that the invariance of choice across conditions indicates that behavior was insensitive to experimental contingencies. For Subjects 203 and 204, however, response rates were greater on the VI schedule across conditions. This finding indicates that responding was sensitive to the different schedule contingencies. For Subject 203, choice was indifferent across conditions and response rates were similar on both the fixed and variable schedules. It is unclear whether these results indicate an absence of experimental control, or no strong preference for either alternative.

For Subject 206, following the first few sessions of the experiment, mean pause durations increased beyond 30 s and remained above 30 s across all conditions during both forced-choice and choice trials. Because the pause durations were greater than 30 s, it is unlikely that changes in the form of the variable distribution influenced choice. Furthermore, because only the long delay intervals of the VI schedule were experienced, the mean obtained delays to reinforcement were much greater on the variable schedule than fixed schedule in both forced-choice and choice trials. The higher mean delay value experienced on the variable schedule could therefore explain the exceptionally strong risk aversion shown in this subject across the experiment. Thus, for Subject 206, choice appeared to be sensitive to the schedule contingencies that were actually experienced during experimental sessions.

Research with nonhumans has shown that mean reinforcement rates calculated by averaging methods that differentially weight short intervals of the variable distribution, (e.g. the harmonic mean) provide a better description of choice patterns than the arithmetic mean. In the present experiment, across all VI distributions the harmonic means of the VI schedule elements were substantially lower than the value of the FI schedule, yet in no condition was the VI schedule

preferred. Thus, the harmonic mean, or any averaging principle that predicts that the VI schedule will have a lower reinforcement rate or higher value than the FI schedule, cannot account for the present results. The arithmetic mean predicts no strong preference for either schedule and thus provides a better description of choice than the harmonic mean, but it only accounts for choice in two of the four subjects. The results are also inconsistent with predictions of models such as scalar expectancy theory (SET) or the expectation of ratios (EoR) that predict that choice should be risk prone across conditions.

Choice patterns were also inconsistent with results of previous research with nonhumans showing that the minimum delay value influences preference. In the present experiment, the minimum delay value of the VI schedule was held constant at 1 s across all distributions. Although choice was unaffected by the form of the variable distribution, the 1-s value was substantially shorter than the FI 30-s schedule value, but in no condition was the VI schedule preferred.

It is possible that choice was not risk prone in the present experiment because delays to reinforcement were too short to produce significant delay discounting. Across all distributions, the delays to reinforcement varied between 1 s and 105 s. Although these delays were similar to those used in experiments with nonhumans, the delays used in previous experiments with humans that have shown delay discounting with hypothetical monetary amounts have been substantially longer (e.g., Christensen et al., 1998; Green, Fry, & Myerson, 1994; Green et al., 1999; Rachlin, Raineri, & Cross, 1991). For example, Green et al. (1999) showed delay discounting with hypothetical outcomes across delays of 1 month to 10 years. Hyten, Field and Madden (1994), found similar results using points exchangeable for real money. In their study, subjects showed a preference for a large point amount over a small point amount when both point amounts were exchangeable for money immediately following the experimental session. When the delay to exchange the large point amount for money was increased to three or six weeks, however, preference reversed in favor

of the small option. These findings suggest that if the mean value of the FI and VI schedules was increased, greater temporal discounting and greater risk proneness may occur. One problem with using long delays, however, is that when delays extend beyond the experimental session, extraneous variables, such as the day of the week on which payment will occur, may interact with choice contingencies (Hyten et al. 1994).

It is also possible that choice would be more risk prone if the choice outcome was a consumable reinforcer, such as food, rather than money. That is, greater delay discounting may occur with consumable reinforcers than with nonconsumable reinforcers. (This issue will be addressed further in the General Discussion). Outside the laboratory, however, humans often do show risk proneness when reinforcers are monetary outcomes. Developing a laboratory procedure that can reliably produce risk proneness in humans with monetary reinforcers thus remains an important goal of human risky-choice research. The purpose of Experiment 3, therefore, was to investigate choice in humans with procedures that model conditions that have produced both risk aversion and risk proneness in nonhumans: changes in an organism's energy budget.

EXPERIMENT 3

ENERGY BUDGETS

Overview

Energy budget refers to the relationship between an organism's energy reserves, short-term energy requirements, and the mean rate of energy gain during a foraging period. An energy budget is positive when the net energy gain will exceed the requirement, and negative when the net energy gain will not exceed the requirement. Behavioral ecologists have shown that changes in energy budget can produce large shifts in risk sensitivity. That is, choice may be risk averse when energy budgets are positive, but risk prone when energy budgets are negative (e.g., Caraco et al., 1980).

Although energy-budget manipulations have been conducted with a variety of different species, no experiments have yet investigated choice in humans across changes in energy budget. This is most likely due to the many ethical issues and practical problems involved with manipulating energy intake with humans, and the lack of suitable alternative procedures. Thus, a primary aim of the present experiment was to develop a procedure for studying risky choice in humans that would model important features of energy-budget procedures without manipulating energy intake. This experiment would not only help assess the generality of energy-budget effects, but could also help clarify the conditions under which choice of humans is risk averse and risk prone.

It will be useful first to provide an overview of energy-budget research. The following section contains a brief description of the theoretical assumptions underlying energy-budget models and the main experimental findings.

Energy-budget Research with Nonhumans

The Energy-Budget Rule

The effects on risky choice of an organism's energy budget are predicted by optimization models developed by behavioral ecologists. Optimization models are based on the assumption that fitness is maximized by optimizing rates of energy gain. In classical optimization models, rate of energy gain is specified as an arithmetic average, calculated by dividing the net energy gain by the total acquisition time (search and handling costs). This method of calculating rates of energy gain implies that the mean rate of energy gain, but not variability in gain, influences choice.

Several behavioral ecologists have argued, however, that foraging choices should be sensitive to variability (i.e., risk sensitive) under some circumstances (Caraco, 1980; Real, 1980). One of the first formal models of risk-sensitive foraging was proposed by Stephens (1981). Unlike most optimization models, this model predicts that fitness is maximized by minimizing the probability of starvation. The model was designed to predict choice in a forager faced with two food options who needs R units of food to survive overnight. Both food options have the same mean value, but different variances. Stephens assumed that only one foraging choice occurred each day. Ignoring expenditures, a forager's daily energy budget was described as:

$$\mu^*n + Sn > R \text{ (positive energy budget)} \qquad (1)$$
$$\mu^*n + Sn < R \text{ (negative energy budget)}$$

where Sn is energy reserves and μ is mean food intake per time interval and n is the number of time intervals in the foraging period.

To predict choice under positive and negative energy-budgets, Stephens (1981) assumed that at the end of a day a forager would have So reserves. This amount, determined by foraging

choices, was distributed normally with mean μ and variance σ^2. Fitness was assumed to be a step-function of reserves. That is, all reserve levels below *So* had a fitness value of zero and all reserves above *So* had the same (non-zero) value. Because *So* was normally distributed, *R* was converted into a *z*-score:

$$z = (R-\mu)/\sigma$$

The probability of survival at the end of the day was then calculated as:

$$P(So>R) = 1-\Phi(z)$$

where $\Phi(z)$ was the cumulative distribution of the normal curve. Because $\Phi(z)$ increases as z increases, when the energy budget is positive, probability of survival is maximized by minimizing variance (i.e., decreasing variance increases z). Conversely, when the energy budget is negative, probability of survival is maximized by maximizing variance (i.e., increasing variance decreases z).

This model, called the extreme variance rule or the *z*-score model (or sometimes the energy-budget rule), can predict choice between options having the same mean value. It can also be extended to cases in which options differ in both their mean values and variances (Stephens & Charnov, 1982). It should be noted that the energy-budget rule, which is based upon overnight survival, is only one type of risk-sensitive foraging model (see McNamara & Houston, 1992). The energy-budget rule will be emphasized here because this model has received the greatest amount of empirical support.

Energy-Budget Experiments

The first experiment to demonstrate shifts in risk-sensitivity with changes in energy budget was conducted by Caraco et al. (1981). Six yellow-eyed juncos were given repeated choices between two feeding stations delivering either a constant or variable number of seeds. The probability distribution of the variable option was bivalued. Daily energy requirements were determined by measuring metabolic rates and the rate of food intake. During positive energy-budget conditions, subjects were deprived of food for 1 hr prior to experimental sessions and seeds were delivered at a mean rate that exceeded daily requirements. During negative energy-budget conditions, subjects were deprived for 4 h and seeds were delivered at a mean rate that fell below daily requirements. Caraco et al. found that choice was risk averse during positive energy-budget conditions and risk prone during negative energy-budget conditions. Thus, energy budget influenced risk sensitivity in a manner consistent with the energy-budget rule.

A number of subsequent studies with fish (Croy & Hughes, 1991; Young, Clayton, & Barnard, 1990), bumblebees (Cartar, 1991; Cartar & Dill, 1990), shrews (Barnard & Brown, 1985), and small birds, including white-crowned sparrows (Caraco, 1983) and dark-eyed juncos (Caraco, 1981), have demonstrated shifts in risk-sensitivity with changes in energy budget (see Bateson & Kacelnik, 1998; Kacelnik & Bateson, 1996; Real & Caraco, 1986; for reviews). For example, Barnard and Brown (1985) estimated daily energy budgets of wild-caught shrews by feeding them ad libitum mealworms and measuring rates of food intake per hour. Shrews were then deprived for 1.5 h and given repeated choices between a constant option delivering 1 food item with certainty and a variable option delivering 0 food items with $p=.67$ or 3 food items with $p=.33$. Energy budgets were manipulated by changing the duration of the ITI. Barnard and Brown showed that the constant alternative was preferred when the energy budget was positive but that the variable alternative was preferred when the energy budget was negative.

Although energy budgets are most often manipulated by changing deprivation levels and rates of reinforcement, a unique study by Caraco, Blanckenhorn, Gregory, Newman, Recer, and Zwicker (1990) manipulated energy requirements of yellow-eyed juncos by changing the ambient temperature. Food consumption was measured at 1° , 10°, and 19° C. These measures showed that total consumption (and thus required energy) varied inversely with temperature. During experimental sessions, the rate of reinforcement equaled the average rate of consumption during the 10° C condition. Thus, during conditions in which the temperature was 1° C, the energy budget was negative, and during conditions in which the temperature was 19° C, the energy budget was positive. Subjects were given repeated choices between options delivering a fixed and variable number of seeds. Choice was risk averse during positive energy-budget conditions and risk prone during negative energy-budget conditions.

Not all experiments that have manipulated energy budgets have found complete shifts from risk aversion to risk proneness as energy budgets were changed from positive to negative. In several studies, only the degree of risk aversion changed (Hamm & Shettleworth, 1989; Ito, Takatsuru, & Saeki, 2000). That is, choice remained risk averse across conditions but became less risk averse under negative energy-budget conditions. Other studies have shown no change in risk sensitivity across changes in energy budget (Battalio, Kagel, & MacDonald, 1985; Banschbach & Waddington, 1994) whereas still others have shown changes in risk sensitivity in the direction opposite to that predicted by the energy-budget rule (e.g., Hastjarjo, Silberberg, & Hursh, 1990; Lawes & Perrin, 1995). Thus, while not consistent with all available data, the energy-budget rule provides an excellent account of risky choice in many species and it makes predictions about the effects of energy budgets no other choice models make (see Bateson & Kacelnik, 1998).

Energy-budget Research with Humans

Field studies

Because energy budgets can be important determinants of risky choice in nonhumans, it is important for both cross-species comparisons and for a better understanding of human behavior to determine whether energy budgets also affect risky choice in humans. A field study by Kunreuther and Wright (1979) has provided at least qualitative support for the energy-budget rule. Rather than devoting their fields entirely to low variance food crops, poor farmers in Bangledesh planted risky cash crops in proportions nearly equal to those of rich farmers. These findings were interpreted in terms of a minimum subsistence requirement (i.e., income level). Kunreuther and Wright argued that very wealthy farmers who were easily able to meet their minimum subsistence requirement planted risky (potentially high-paying) crops. Middle income farmers who had a moderate risk of failing to meet their minimum requirement preferred low variance food crops. The low-income farmers, however, who had the largest probability of not meeting their minimum requirement planted riskier crops to avoid poverty. If the crop returns did not meet their minimum requirement, they were forced to borrow money from others or face starvation.

Although these findings are broadly consistent with the energy-budget rule, field studies lack the quantitative rigor needed for strong tests of the model. That is, in the field it is difficult to manipulate and assess variables that determine energy budget and it is often not practically feasible to eliminate extraneous variables. In the laboratory, however, variables can be carefully controlled, permitting more precise tests of optimality models such as the energy-budget rule. As described above, no laboratory studies have yet manipulated energy budgets in humans, possibly owing to the ethical difficulties of establishing negative energy budgets. It may be possible, however, to study choice in humans under non life-threatening conditions with a experimental procedure that models energy-budget manipulations.

Hypothetical life-death choices

Several researchers have attempted to model risky choice in humans in life-threatening situations by presenting subjects with choices between hypothetical life-death options (e.g., Wang, 1995, 1996a, 1996b; Wang & Johnston, 1995). Wang and Johnston (1995) and Wang (1996a), for example, presented subjects with hypothetical choices between saving the lives of either a certain or variable number of people as the size of the hypothetical group was manipulated. Both studies showed that choice was more risk seeking when the group size was small than when the group size was large. Wang interpreted these results in terms of the subjects' own survival, arguing that throughout human history, an individual's own chance of survival was directly related to the survival of a minimum number of people in the individual's social group. Thus, if an individual was faced with a risky choice involving the life and death of members of their social group, choice should be risk prone if choice of the certain option would fail to save a sufficient number of people. Wang (1996b) compared the results of these studies to those found in risk-sensitive foraging experiments, noting that whenever an organism is faced with a risky choice involving a life-death decision, choice should be risk seeking if choice of the certain outcome could lead to the individual's own death.

Although the results of these studies show that risky choice in humans may be influenced by variables related to survival, the procedures are limited in their ability to model energy-budget procedures. First, the life-death outcomes are necessarily hypothetical. It is unclear whether hypothetical outcomes produce the same patterns of risk sensitivity as real outcomes, particularly when outcomes are related to survival. Second, because minimum requirements are not assessed or manipulated prior to the presentation of choice options, it is difficult to predict whether risk

proneness or risk aversion should occur. Because of these limitations, procedures using hypothetical life-death choices may be unsuitable for studying energy-budget effects in humans.

Monetary outcomes

One alternative to using hypothetical life-death choices to study the effects of energy budget with humans is to use real outcomes, such as money, that are not important for immediate survival. That is, it may be possible to conduct the same types of experimental manipulations with humans as conducted in energy-budget experiments with nonhumans using money rather than energy as a consequence.

For example, one might manipulate energy budgets by changing the rate of reinforcement. Rachlin et al. (1986) presented subjects with ten choices between two options delivering hypothetical amounts of money with a high and low probability. Trials for half of the subjects were presented with no ITI whereas trials for the other half of the subjects were separated by a 1.5 min ITI. Because decreasing the rate of trial presentations produces concomitant changes in rates of reinforcement, choice should be risk averse when trials are presented at a high rate (i.e., positive energy-budget conditions) and risk prone when trials are presented at a low rate (i.e., negative energy-budget conditions). Contrary to these predictions, choice of subjects in the long ITI group was more risk-averse than choice of subjects in the short ITI group. Experiments by Rachlin and Siegel (1994) and Silberberg et al. (1988) showed similar effects.

Another way to model changes in energy-budget would be to manipulate monetary holdings (i.e., reserves). Using a procedure similar to that of Rachlin et al. (1986), Silberberg et al. (1988) presented 40 undergraduates with choices between two options delivering a hypothetical amount of money with either a high or low probability. Half of the subjects were told that they would start the experiment with a hypothetical $10, and half were told that they would start with a

hypothetical $10,000. Because presenting large amounts of money increases reserves, choice of subjects in the $10,000 group should be more risk averse than choice of subjects in the $10 group. Across trials, choice patterns were inconsistent with these predictions: Choice of subjects in the $10,000 was less risk averse than choice of subjects in the $10 group.

The risk aversion shown in these experiments is inconsistent with what would be predicted by analogous energy-budget manipulations. However, these experiments were not designed to model energy-budget effects and it unclear whether conditions analogous to positive and negative energy budgets were actually produced. Energy budgets are defined in terms of the relationship between energy reserves, rates of energy intake, and energy requirements. In the Rachlin et al. and Silberberg et al. experiments, although rate of reinforcement (analogous to rates of food delivery) and monetary holdings (analogous to energy reserves) were manipulated, variables analogous to energy requirements were not assessed. Without assessing requirements, it is impossible to determine whether changes in reinforcement rate, or the receipt of $10 or $10,000 (even if actually delivered to subjects) would create conditions analogous to positive or negative energy budgets. Thus, the present experiment attempted to model energy-budget procedures by substituting monetary earnings, monetary reserves, and a monetary earnings requirement for energy gains, energy reserves, and a daily energy requirement.

Dynamic Optimization Models

Because the energy-budget rule predicts only one pattern of risk sensitivity across an entire foraging period (i.e., exclusive preference for the fixed or variable options), it has been called a static optimization model (see Kacelnik & Bateson, 1996; Krebs & Kacelnik, 1991). It has been argued, however, that switching between the fixed and variable options as a function of current energy gains may sometimes be a better strategy than persisting with a single choice option (e.g.

Houston, 1991; Houston & McNamara, 1982; McNamara & Houston, 1987; Real and Caraco, 1986). For example, if a forager whose energy-budget is currently negative experiences a period of high gain, then switching from the variable option to the fixed option may increase the probability of survival. Thus, another goal of the present research was to provide a detailed analysis of choice patterns in humans within, as well as across, choice periods.

Current energy budget can be regarded as a state variable. When choice varies as a function of current state, and state varies as a function of previous choices, then a dynamic optimization model, rather than a static model, is required to predict optimal choice patterns (Houston & McNamara, 1988; Mangel & Clark, 1988). Because dynamic optimization models are designed to predict local regularities in choice patterns, they provide a more detailed description of behavior than static models designed to predict more global outcomes (Krebs & Kacelnik, 1991). The major features of dynamic optimization modeling are outlined briefly below.

As with static optimization models, an important feature of a dynamic optimization model is the function relating fitness to the organism's state at the end of a time period, called the <u>terminal fitness function</u>. Once the terminal fitness function is specified, the total time period over which choice is assessed, *T*, is divided into *n* discrete time intervals, denoted by *t*, during which a choice occurs. Because the optimal choice at each value of *t* and each state (i.e., level of energy reserves), *x*, depends on the outcome of future choices, optimal choices are computed backwards from *T-1* to *T-n*. That is, at each state, optimal choice is first computed during the final time interval, *T-1*, by determining which choice yields the highest fitness value.

Optimal choice is determined by the state dynamics proposed in a particular model. The state dynamics are the calculations that determine the expected change in state for each choice option at the current state value. The state dynamics include variables such as the mean gain, probability of gain, and cost. The fitness value associated with each state at *T-1* is provided by the

terminal fitness function. The choice option yielding the highest fitness is designated as the optimal choice. At *T-2*, the optimal choice at each state is computed by determining which choice option yields the highest expected fitness at *T-1*, assuming that at *T-1* the optimal choice occurred. These calculations are continued for each preceding time interval, producing an optimal choice matrix, sometimes called the optimal policy, which lists the optimal choice for each (t, x) combination (Houston & McNamara, 1988).

McNamara and Houston (1987, 1992) have described an optimal policy of a forager needing sufficient reserves to survive overnight. In their example, the two choice options had identical means, but different variances. The terminal fitness function was assumed to be a step function, with fitness being 0 if reserves were below requirements and 1 if reserves were above requirements. They reported that the optimal policy could be described in terms of a switching line specified by:

$$x + \mu(T-t) = R \qquad (2)$$

where x is the current state, μ is the mean rate of energy gain per time interval, T is the total number of time intervals, t is the current time interval, and R is the energy requirement. In a plot of reserves versus time, risk aversion is optimal above this line and risk proneness is optimal below this line.

This model (Equation 2) is similar to the energy-budget rule (Equation 1). The primary difference between these models is that the energy-budget rule predicts only a single choice at the start of the foraging period, but the dynamic model predicts choice across the foraging period.

Whether static or dynamic models are used to predict choice depends on the choice context (Bateson & Kacelnik, 1998). The static model is better suited to predict single choices, such as the

choice of a food patch, whereas the dynamic models is better suited to predict sequences of choices, such as choice of food items within a patch.

Dynamic optimization models may also be used to calculate the fitness costs (i.e., loss in fitness) from choosing the non-optimal alternative (Houston & McNamara, 1988; McNamara & Houston, 1986). This cost, called the canonical cost, is calculated by subtracting the expected terminal-fitness value of the non-optimal choice from the expected terminal-fitness value of the optimal choice. If the optimal choice is selected, the canonical cost is zero. This comparison is useful because behaving sub-optimally may be more costly at some time and state values than others. McNamara and Houston argued that the canonical cost provides a common scale by which different choices, even those with different types of consequences (e.g. food or predator avoidance), can be evaluated.

Kacelnik and Bateson (1996) have noted that it is difficult to make quantitative predictions about optimal behavior from risk-sensitive foraging models. In most experiments, there are a number of uncontrolled variables. For example, it is often difficult to determine precisely energy gains and energy expenditures. Furthermore, it is difficult to determine the extent to which shifts from risk aversion to risk proneness influence fitness.

One advantage of laboratory procedures is that because the current state (accumulated earnings), the energy gain (reinforcer magnitude), the energy requirement (earnings requirement), the energy budget, and the terminal fitness function (total earnings), can be precisely specified and measured, exact predictions can be made about optimal responding. Thus, in the present experiment, a dynamic optimization model was developed to predict sequences of choices within a choice period. Choices were evaluated both in relation to the predictions of the dynamic model, and in relation to the canonical cost of choosing the non-optimal alternative.

Specific Rationale for Experiment 3

A primary goal of Experiment 3 was to develop a procedure with monetary outcomes to investigate risky choice in humans across manipulations analogous to those used to in energy-budget experiments with nonhumans. The results of this experiment should be relevant not only to cross-species generalities of risky choice, but also to energy-budget models designed to predict optimal choice in foragers.

Humans were given choices between options that delivered a fixed and variable number of points exchangeable for money. Choices were presented in blocks of five trials designed to simulate a daily foraging period. To model a daily energy requirement, a monetary earnings requirement was arranged for each choice period. At the end of a choice period, if the earnings requirement was met, the subject was allowed to keep the accumulated earnings. If the earnings requirement was not met, the earnings were lost. Meeting, or failing to meet, the earnings requirement thus produced consequences that modeled the binary life-death outcomes of meeting or failing to meet a daily energy requirement. Similar to energy-budget experiments conducted with nonhumans, during positive energy-budget conditions exclusive preference of the fixed option would meet the earnings requirement, but during negative-energy-budget conditions exclusive preference of the fixed option would not meet the earnings requirement. With this arrangement, it was possible to examine the predictions of the energy-budget rule with humans. If choice in humans is consistent with the model's predictions, choice would be risk averse during positive energy-budget conditions and risk prone during negative energy-budget conditions.

Another purpose of the present experiment was to analyze within-block choice patterns by comparing choices to the predictions of a dynamic optimization model. Thus, a dynamic

optimization model was constructed to predict optimal choices across trials of a block as a function of accumulated points.

As in Experiments 1 and 2, choice outcomes were real. In addition, because Experiment 1 showed that choice between fixed and variable reinforcer amounts was not influenced by the form of the variable distribution, only the bivalued distribution was used.

Method

Subjects

The participants were three adult humans recruited via an advertisement in a local university newspaper. Subject 331 was a 20 year-old male and Subjects 331 and 332 were both 22 year-old females. None had any previous experience with behavioral research. Point earnings were exchanged for cash immediately following each session. Subjects were also given a receipt after each session in the amount of $1.50. At the termination of the experiment, a check for the sum of these receipts was mailed to the subject. Overall earnings averaged near $6.00 per hour.

Apparatus

The apparatus was the same as in Experiment 1 (with the modifications described for Subject 218) except that the 4-digit electromechanical counter was replaced by a 6-digit electrical counter measuring 3 cm by 6 cm, and a second, identical counter was mounted 1.8 cm below it.

Procedure

A session consisted of 12 blocks of five trials. The first six blocks of a session were forced-choice trials and the second six blocks were choice trials. At the start of each block, the top (trial) counter was set to zero. The start of each trial was signaled by the illumination of the center key. During choice blocks, a single response on the red center key extinguished the keylight and illuminated both side keys which flashed according to a 0.25 s on-off cycle. The fixed and variable

alternatives were correlated with yellow and green keylights, respectively. Five responses on one of the keys extinguished both keylights and produced points. If the fixed option had been selected, two points were added to the trial counter and if the variable option had been selected, one or three points ($p=.5$) were added to the trial counter. The key position of the fixed and variable option was randomly determined each trial. Following point delivery on the fifth trial of a block, if the number of points on the trial counter equaled or exceeded the point requirement, the points on the trial counter were added to the lower (block) counter. If the number of points on the trial counter was less than the point requirement, no points were added to the block counter. The trial counter was then reset and the next block began immediately.

Forced-choice blocks were similar to choice blocks except that only one keylight was illuminated and across all five trials only the fixed or variable option was presented. The schedule type was randomly determined each block with the restriction that three blocks presented only the fixed option and three blocks presented only the variable option. Across forced-choice and choice trials, pressing a dark key or switching between keys reset the FR 5 schedule, such that five consecutive responses were required to produce points.

The point requirement was manipulated across conditions. During Positive Energy-Budget conditions, the point requirement was 10 points ($R=10$). Under these conditions, exclusive preference for the fixed option would meet the requirement; exclusive preference for the variable option would meet the requirement half the time, on average. During Negative-Energy Budget conditions, the point requirement was either 12 points ($R=12$) or 13 points ($R=13$). Exclusive preference for the fixed option would not meet the requirement under either of these conditions; exclusive preference for the variable option would occasionally meet the criterion (.19 probability).

The following instructions were posted to the right of the response panel and were read to the subject prior to the first experimental session:

> You may earn points by pressing the response keys when lit. Press only one key at a time. Each point displayed on the lower, right counter is worth 2.5¢. Please remain seated. You will be informed when the session is over.

Table 3 shows the sequence and number of sessions per condition for each subject. All subjects were first exposed to Positive Energy-Budget (R=10) conditions. Conditions were changed after a minimum of five sessions and when the number of choices for the fixed option was stable across a three-session block, as determined by visual inspection. Sessions were conducted at approximately the same hour, Monday through Friday. Typically, two sessions were conducted daily with sessions separated by a brief (approximately 2 min) break.

Because Subject 333 showed little sensitivity to energy-budget contingencies during the first exposure to Positive (R=10) and Negative Energy-Budget (R=13) conditions, during the second replication of the Positive Energy-Budget (R=10) condition the number of forced-choice blocks per session was increased from six to ten. Across sessions, the number of forced-choice blocks was gradually reduced, and across the final five sessions of the condition the number of forced-choice blocks was six.

Table 3

Sequence and number of sessions per condition for each subject in Experiment 3.

Energy-budget Condition	Subject 331	Subject 332	Subject 333
Positive (R=10)	1 (10) 3 (19)	1 (7) 3 (12)	1 (9) 3 (16) 5 (6)
Negative (R=12)	2 (8)	2 (6)	
Negative (R=13)	4 (5)	4 (5)	2 (10) 4 (7)

Results

Across-block choices

Figure 8 shows the mean number of choices for the fixed option across the final three sessions of positive and negative energy-budget conditions. The horizontal line indicates the indifference point between the two options and the vertical lines show standard deviations. For all subjects, the across-block choices showed sensitivity to energy-budget conditions. Subjects 331 and 332 showed a similar pattern of responding. During the first exposure to the Positive Energy-Budget (R=10) condition, choice was strongly risk averse. The mean number of choices for the fixed option during the final three sessions of the condition was approximately 29.3 and 29.0 for Subjects 331 and 332, respectively. Choice was also risk averse during the second exposure to Positive Energy-Budget (R=10) conditions, but there was greater session-to-session variability in choices. Across the final three sessions, the mean number of choices for the fixed option for these two subjects was 28.0 and 22.7, respectively. Choice was risk prone during both exposures to negative energy budget conditions. During the Negative Energy-Budget (R=12) condition, the number of choices for the fixed option for Subjects 331 and 332 was 13.3 and 12.3, and during the Negative Energy-Budget (R=13) condition, in which the point requirement was most stringent, the mean number of choices for the fixed option was 6.7 and 4.7, respectively.

Choice of Subject 333 was also sensitive to positive and negative energy-budget conditions, but the sensitivity was somewhat weaker than in the other two subjects. During the first exposure to both the Positive Energy-Budget (R-10) condition and the Negative Energy-Budget (R-13) condition, the number of choices for the fixed option was similar. Across the final three sessions of these conditions, the mean number of choices for the fixed option was 17.7 and 17.0, respectively. Thus, during the second replication of the Positive Energy-Budget (R=10) condition, the number of forced-choice trials was increased to 50 for several sessions, and was then

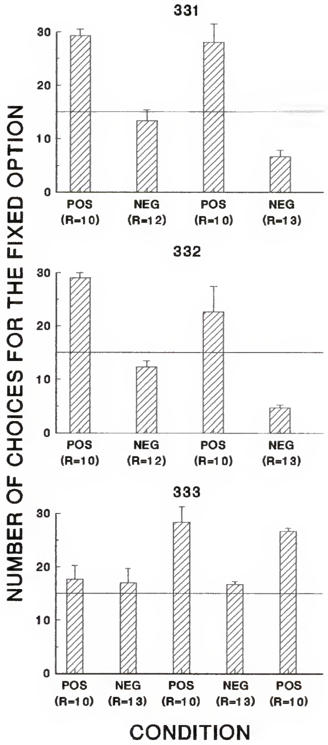

Fig. 8. Mean number of choices for the fixed option per session across the final three sessions of positive (POS) and negative (NEG) energy-budget conditions for each subject in Experiment 3. Vertical lines show standard deviations. The horizontal line indicates the indifference point between the two options.

gradually decreased across sessions to its original value of 30. This manipulation produced greater sensitivity to energy-budget contingencies. Across the final three sessions of the subsequent two exposures to Positive Energy-Budget (R=10) conditions, the mean number of choices for the fixed option was 28.3 and 26.5, comparable to the other two subjects. The number of choices for the fixed option decreased during the Negative Energy-Budget condition (R=13), although choice remained slightly risk averse. During the final three sessions, the mean number of choices for the fixed option was 16.7.

Figure 9 shows the mean number of points earned during choice trials across the final three sessions of each condition. Point earnings varied substantially across positive and negative energy-budget conditions. For Subjects 331 and 332, point earnings were high during both exposures to Positive Energy Budget (R=10) conditions. During the first exposure, the mean number of earned points was 60.0 for both subjects, but was slightly lower during the second exposure due to the greater number of variable choices. Point earnings were much lower during both negative energy-budget conditions. The mean number of earned points was 28.0 and 45.0 across the final three sessions of the Negative Energy-Budget (R-13) condition, and 17.3 and 8.7 across the final three sessions of the Negative Energy-Budget (R-12) condition for Subjects 331 and 332, respectively.

For Subject 333, because choice showed little sensitivity to energy-budget contingencies during the first exposures to both the Positive Energy Budget (R=10) and Negative Energy-Budget (R=13) conditions, point earnings were lower than for the other two subjects. During the subsequent two exposures to Positive Energy-Budget (R=10) conditions, however, mean point earnings were also high, averaging 57.0 and 54.0 points across the final three sessions. During the final exposure to the Negative Energy-Budget (R=13) condition, point earnings were very low, and across the final three sessions, no points were earned.

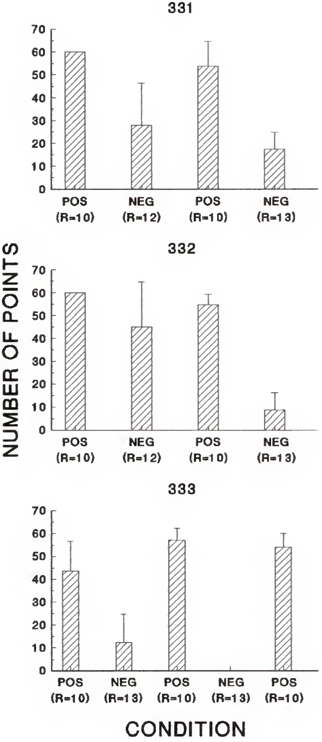

Fig. 9. Mean number of points earned during choice trials across the final three sessions of positive (POS) and negative (NEG) energy-budget conditions for each subject. Vertical lines show standard deviations.

Within-block choices

The number of fixed and variable choices and the number of accumulated points across successive trials of a block is shown in Appendix A for each subject over the final three sessions of a condition. The within-block choice patterns were analyzed in accordance with the predictions of a dynamic optimization model. The model generated expected earnings for fixed and variable choices at each number of accumulated points for each trial of a block. The choice sequence yielding the highest expected earnings was designated as the optimal choice. (A description of how the model generated expected earnings, and thus optimal choices, is presented in Appendix B).

Tables 4, 5, and 6 show the expected earnings associated with selecting the fixed and variable option at each number of accumulated points during each trial of a block for the Positive-Energy Budget (R=10), Negative-Energy Budget (R=12), and Negative-Energy Budget (R=13) conditions. The optimal choice at each trial within a block is underlined. The final column in each table shows the values of the terminal fitness function, designated *R*(x). The terminal fitness function specified that the number of points earned at the end of a block would equal zero if the number of accumulated points was below the requirement, and would equal the point earnings if the number of accumulated points was equal or greater than the requirement. The maximum value of *R*(x) was 15--the maximum number of points that could be earned per block. Overall, the tables show that, consistent with the model described by McNamara and Houston (1987), preference for the risky option was predicted only when the expected earnings were below the requirement. Preference for the fixed option was predicted when the expected earnings equaled the requirement. When the expected earnings of the fixed and variable option were identical, no particular choice was designated as optimal.

Also included in Tables 4, 5, and 6 are the canonical costs, or the losses in expected point earnings from choosing the non-optimal choice. These values were calculated by subtracting the

Table 4

Expected point earnings for selections of the fixed (F) and variable (V) option at each number of accumulated points for the Positive Energy-Budget (R=10) condition. The optimal choice is underlined. *R(x)* indicates the terminal fitness function (the number of points delivered for each number of accumulated points following the fifth trial). Also shown is the canonical cost (loss in point earnings) of selecting the non-optimal choice.

	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Points	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	*R(x)*
0	<u>10</u>	8.63	1.37													0
1				6.25	6.25											0
2				<u>10</u>	8.63	1.37	2.5	2.5								0
3				11	11		5	<u>6.25</u>	1.25	0	0					0
4							<u>10</u>	8	2	0	<u>2.5</u>	2.5	0	0		0
5							11	11		5	5		0	0		0
6							12	12		<u>10</u>	8	2	0	0		0
7										11	11		0	<u>5</u>	5	0
8										12	12		<u>10</u>	5.5	4.5	0
9										13	13		11	11		0
10													12	12		10
11													13	13		11
12													14	14		12
13																13
14																14
15																15

Table 5

Expected point earnings, canonical costs, and terminal fitness function, *R(x)*,for the Negative Energy-Budget (R=12) condition. All other details as in Table 4.

	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Points	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	*R(x)*
0	4.5	4.5														0
1				1.5	1.5											0
2				3	4.5	1.5	0	0								0
3				7.5	7.5		0	1.5	1.5	0	0					0
4							3	3		0	0		0	0		0
5							6	7.5	1.5	0	0		0	0		0
6							12	9.5	2.5	0	3	3	0	0		0
7										6	6		0	0		0
8										12	9.5	2.5	0	0		0
9										13	13		0	6	6	0
10													12	6.5	5.5	0
11													13	13		0
12													14	14		12
13																13
14																14
15																15

Table 6

Expected point earnings, canonical costs, and terminal fitness function, *R(x)*, for the Negative energy-budget (R=13) condition. All other details as in Table 4.

	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Points	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	*R(x)*
0	.63	2.84	2.21													0
1				0	0.81	.81										0
2				1.63	1.63		0	0								0
3				3.25	4.88	1.63	0	0		0	0					0
4							0	1.63	1.63	0	0		0	0		0
5							3.25	3.25		0	0		0	0		0
6							6.5	8.13	2.47	0	0		0	0		0
7										0	3.25	3.25	0	0		0
8										6.5	6.5		0	0		0
9										13	10.25	2.75	0	0		0
10													0	6.5	6.5	0
11													13	7	6	0
12													14	14		0
13																13
14																14
15																15

expected earnings of non-optimal choice from the expected earnings of the optimal choice. If choice was sensitive to the differential outcomes of choosing optimal and non-optimal choices, then deviations from the optimal pattern should vary inversely with the cost of such deviations.

Tables 7, 8, and 9 show for each subject the proportion of total choices consistent with the model's predictions at each trial and point combination for each condition. Only choices from the final three sessions of a condition are included. Overall, choices were generally consistent with model's predictions. For the two subjects showing the greatest sensitivity to energy-budget conditions (Subjects 331 and 332), the within-block choices were similar. The proportion of choices consistent with predictions were frequently high, but choices were more consistent with predictions during the Positive Energy-Budget (R=10) than during the Negative Energy-Budget (R=12) and Negative Energy-Budget (R=12) conditions. Across all conditions, choices became more consistent with the model's predictions across trials within a block. In other words, choices were more likely to deviate from the optimal pattern earlier than later in a block. The patterns of deviations were also similar for these two subjects. Most deviations in positive energy-budget conditions were the result of variable choices early in the block when preference for the fixed option was predicted, and most deviations in negative-energy-budget conditions were the result of choices for the fixed option early in the block when preference for the variable option was predicted.

For Subject 333, within-block choices are presented only for two Positive Energy-Budget (R=10) conditions and the one Negative Energy-Budget (R=13) condition that followed the additional exposure to the forced-choice trials. Within-block choices were generally consistent with predictions during the Positive Energy-Budget (R=10) conditions, but were often inconsistent with predictions during the Negative Energy-Budget (R=13) conditions. Choices showed only a slight tendency to become more consistent with predictions across a block. The pattern of deviations is also more difficult to characterize for this subject. In both positive and negative

Table 7

Proportion of fixed (F) and variable (V) choices consistent with the model's predictions across the final 3 sessions of a condition for each trial of a block and number of accumulated points for Subject 331.

	Requirement = 10 (first exposure)										Requirement = 10 (second exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	.94										.94									
1																				
2			1.0										.94							
3																				
4					1.0										1.0					
5																				
6							1.0										.94			
7																				1.0
8									1.0										1.0	
9																				
10																				
11																				
12																				

Table 7 cont.

	Requirement = 12										Requirement = 13									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0												.89								
1														1.0						
2				.67																
3						1.0								1.0						
4																1.0				
5						1.0														
6					1.0			1.0								.33				
7																		1.0		
8							1.0													
9										1.0										
10									1.0											1.0
11																			1.0	
12																				

Table 8

Proportion of fixed (F) and variable (V) choices consistent with the model's predictions across the final 3 sessions of a condition for each trial of a block and number of accumulated points for Subject 332.

	Requirement = 10 (first exposure)										Requirement = 10 (second exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	.94										.83									
1																				
2			1.0										.86							
3																1.0				
4					1.0										.86			1.0		
5																				
6							1.0										.92			
7																				1.0
8									1.0										1.0	
9																				
10																				
11																				
12																				

Table 8 cont.

	Requirement = 12										Requirement = 13									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0												.72								
1				.57										1.0						
2						1.0														
3														.4						
4						.56										1.0				
5					.50			.50												
6																.5				
7							1.0											1.0		
8										1.0										
9									1.0											
10																				1.0
11																			1.0	
12																				

Table 9

Proportion of fixed (F) and variable (V) choices consistent with the model's predictions across the final 3 sessions of a condition for each trial of a block and number of accumulated points for Subject 333.

	Requirement = 10 (second exposure)										Requirement = 10 (third exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	1.0										.78									
1																				
2			.89										.93							
3						0														
4					1.0										1.0			0		
5																				
6							1.0										1.0			
7																				1.0
8									.94										1.0	
9																				
10																				
11																				
12																				

Table 9 cont.

	Requirement = 13 (second exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V
0	.44									
1				.60						
2										
3				.33						
4						.44				
5										
6						0				
7								1.0		
8										
9										
10										0
11										
12										

energy-budget conditions, deviations were the result of both choices for the fixed option when preference of the variable option was predicted, and variable choices when preference for the fixed option was predicted.

Within-block choice patterns were evaluated in relation to the canonical cost measures by plotting the proportion of choices consistent with predictions as a function of the canonical cost of choosing the non-optimal choice. These results are shown in Figure 10. Overall, choice of Subjects 331 and 332 showed that choice was more consistent with predictions at higher than lower canonical costs. This trend was less apparent for Subject 333. For this subject, the proportion of choices consistent with predictions showed little relation to canonical cost.

Discussion

Choice for all subjects was sensitive to energy-budget conditions. For the two subjects showing the greatest sensitivity to energy-budget conditions (Subjects 331 and 332), choice was risk averse during positive energy-budget conditions and risk prone during negative energy-budget conditions. Furthermore, choice was more risk prone during the Negative-Energy Budget (R=13) condition, in which the point requirement was more stringent, than during the Negative-Energy-Budget (R=12) condition. For Subject 333, choice was risk averse during two of the three exposures to the Positive Energy-Budget (R=10) condition. Choice remained risk averse during the Negative-Energy Budget (R=13) conditions, but the number of choices for the fixed option was lower than during the Positive Energy-Budget (R=10) conditions. Thus, although choice for Subject 333 did not show complete shifts from risk aversion to risk proneness across changes in energy budget, choice shifted in the same direction as in the other two subjects. Choices for Subject 333 were therefore qualitatively consistent, and choices for Subjects 331 and 332 were quantitatively consistent, with the predictions of the energy-budget model.

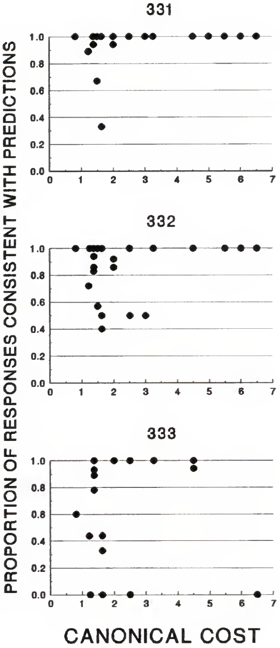

Fig. 10. Proportion of within-block responses across the final three sessions of each energy-budget condition that were consistent with the predictions of an optimization model plotted as a function of the canonical cost of selecting the non-optimal alternative. Values for each subject are shown.

The within-block choice patterns also showed sensitivity to the energy-budget contingencies. Choices were generally consistent with the predictions of a dynamic optimization model, especially for Subjects 331 and 332, indicating that choices were optimal not only at the global level but also at the more local level of individual choices. Because the model's predictions were determined by the number of accumulated points, the number of points produced by fixed and variable choices, the position within the block, and the point requirement, these results show that, for at least two subjects, choice was simultaneously sensitive to all of these variables. These results also showed that across-block choice patterns in positive and negative energy-budget conditions were not the result of general risk-averse or risk-prone preferences, but were the result of specific within-block choices.

For Subjects 331 and 332, although choices occasionally deviated from the predictions of the optimization model, the deviations were systematically related to the canonical-cost measures. When deviating from the optimal pattern was not very costly (i.e., early in the block), the proportion of choices consistent with predictions was lower than when deviating from the optimal pattern was more costly (i.e., later in the block). These results thus suggest that within-block choice patterns were sensitive to the differential (point) consequences of selecting the fixed and variable option.

Mean point earnings per session also showed that choice patterns frequently maximized reinforcement rates. During both negative energy-budget conditions, exclusive preference for the variable option would meet the requirement with $p=.19$, and thus produce an average of 11.3 points. As a result of switching between fixed and variable choices during negative energy-budget conditions, however, point earnings were often higher than this value, especially for Subjects 331 and 332. For example, assuming that choice would switch from the variable to the fixed option following the receipt of two, 3-point variable outcomes during Negative Energy-Budget (R-12)

conditions, the predicted probability of exceeding the point requirement increases to p = .38. Similarly, assuming that choice would switch from the variable to the fixed option following the receipt of three, 3-point variable outcomes during Negative Energy-Budget (R=13) conditions, the predicted probability of exceeding the point requirement increases to p=.22. With this pattern of switching, during the Negative-Energy Budget (R=12) and Negative-Energy Budget (R=13) conditions, the predicted mean point earnings increases to 22.5 points and 13.4, respectively. For two subjects (Subjects 331 and 332), obtained point earnings were in most cases closer to these values. That switching between alternatives could yield higher point earnings than exclusive preferences is consistent with suggestions made by behavioral ecologists that switching between fixed and variable options can yield higher measures of fitness (e.g., Houston & McNamara, 1982).

The present results are analogous to those shown in energy-budget research with nonhumans (e.g. Barnard & Brown, 1985; Caraco et al., 1980). Of particular relevance to the present study are the results of an experiment by Caraco et al. (1990). In their study, choice was risk averse when energy requirements were low (positive energy-budget conditions), but choice was risk prone when energy requirements were high (negative energy-budget conditions). Similarly, in the present study choice was risk averse when the point requirement was low (positive energy-budget conditions), and more risk prone when the point requirement was high (negative energy-budget conditions). Additional research is required to determine whether the same shifts in risk sensitivity can be produced in humans by the more common methods of changing energy budget: Changing the rate of reinforcement (i.e., changing the point earnings on the fixed and variable option), and changing energy reserves (i.e., changing points available at the start of each block).

Several points concerning the use of dynamic optimization models deserve comment. First, dynamic optimization models have been criticized on several grounds, including their complexity (see commentary on Houston & McNamara, 1988). For example, Smith (1988) has

noted that although dynamic models can offer greater realism than static optimization models, because their predictions are based upon multiple independent variables, they are much more difficult to test. Testing dynamic optimization models, Smith argued, may be more feasible in operant procedures. The analyses presented here provide some additional support for this statement. That is, the within-block choice analyses showed that when behavioral contingencies are well controlled, choices could be readily evaluated in relation to the predictions of a dynamic model. Second, these analyses suggest that dynamic optimization models may be useful for operant analyses of behavior. In the present experiment, complex, within-block choice patterns were often well described by the predictions of a dynamic optimization model whose main assumption was that choices would maximize reinforcement rates. Thus, dynamic optimization models may be useful for describing and predicting dynamic behavior patterns resulting from the interaction of prior consequences and current reinforcement contingencies. Furthermore, that deviations from optimal choices were often related to the costs of selecting the non-optimal alternative (canonical-cost measures) suggests that dynamic models may be used to predict the conditions under which non-optimal behavior may occur. That is, deviations from optimality may be more likely when canonical costs are low than when they are high.

GENERAL DISCUSSION

The present experiments examined the generality of results of previous risky-choice research with humans by investigating choice under conditions more similar to those used with nonhumans. Specifically, subjects were given relatively extensive exposure to choice contingencies when choices produced real monetary outcomes. Experiments 1 and 2 examined choice between fixed and variable reinforcer amounts and delays, respectively, as the form of the variable distribution was manipulated across conditions. In both experiments, choice was either risk averse or risk neutral. These results are generally consistent with previous research with humans, demonstrating that patterns of risk sensitivity obtained in studies using hypothetical outcomes and verbally described contingencies generalize to situations in which choice outcomes are real and choice contingencies are actually experienced.

Experiment 3 examined choice between fixed and variable reinforcer amounts across experimental manipulations designed to model energy-budget manipulations conducted with nonhumans. Unlike the results of the first two experiments, risk sensitivity varied systematically across conditions. Choice was risk averse during positive energy-budget conditions but frequently risk prone during negative energy-budget conditions. These results suggest that the consistent risk aversion shown in previous research with humans may be due in part to the procedures typically used to assess choice.

A number of researchers have commented on the advantages of studying human behavior under conditions resembling those used with nonhumans (e.g. Baron, Perone, & Galizio, 1991; Hackenberg, 1998; Kollins, Newland, & Critchfield, 1997). For example, Baron et al. have

argued that giving human subjects prolonged exposure to contingencies (similar to studies with nonhumans) may increase control of behavior by current reinforcement contingencies and reduce control by extraneous variables. The results of Experiments 1 and 2 provide some support this assumption. In many cases, patterns of risk sensitivity obtained during initial conditions of the experiment were more variable and sometimes very different than patterns obtained during subsequent conditions, suggesting that experience with choice contingencies influenced responding. If choice had been evaluated across a few sessions or choice trials, the conclusions would have been very different.

Despite the extensive exposure to choice contingencies, the risk sensitivity obtained in the present research was not always consistent with the risk sensitivity shown in nonhumans. That is, although the risk aversion obtained in Experiment 1 was comparable with the results of some studies with nonhumans, the risk aversion and risk neutrality shown in Experiment 2 contrasted with the strong risk proneness shown in previous studies with nonhumans. This finding suggests that other procedural differences between the present experiments and experiments conducted with nonhumans may be important.

One procedural variable that may have contributed to the differences in responding concerns the nature of the reinforcer. Although the present research used real money as an outcome, it is likely that delays to money (a nonconsumable reinforcer) do not have the same effect on choice as delays to food (a consumable reinforcer). Previous research has shown that when presented with choices between a small amount of food delivered after a delay, nonhumans strongly prefer the immediate option (e.g., Rachlin & Green, 1972). Analogous studies with humans using monetary reinforcers have shown the opposite effect (e.g., Logue, Peña-Correal, Rodriguez, & Kabela, 1986). Several experiments with humans using consumable reinforcers, however, such as food deliveries (Forzano & Logue, 1994; Logue & King, 1991) or access to a pre-recorded TV

program (Navarick, 1996), have shown greater sensitivity to reinforcer immediacy. For example, a recent study in our laboratory using access to a pre-recorded TV program as a reinforcer showed that adult humans preferred more immediate access to a smaller reinforcer (a 20-s video segment) to delayed access to a larger reinforcer (a 60-s video segment) (Hackenberg & Pietras, 2000). Together, these studies suggest that greater delay discounting occurs when choice outcomes are immediately consumable reinforcers than when they are nonconsumable reinforcers. Because delay discounting is thought to underlie the preference for variable over fixed delays to reinforcement in nonhumans, it is possible that choice of humans would also show greater risk proneness when choice outcomes are consumable reinforcers.

Although investigating choice in humans with consumable reinforcers is an important direction for future risky-choice research, there are a number of advantages to studying human risk taking using monetary reinforcers. Many examples of human risk taking outside the laboratory involve monetary reinforcers (e.g., gambling or playing the stock market). Using monetary reinforcers may therefore facilitate the development of laboratory models that generalize more readily to circumstances outside the laboratory. In addition, results of experiments using monetary reinforcers can be integrated with a substantial amount of risky-choice research conducted by economists, cognitive psychologists, and researchers interested in decision making, the majority of which has been concerned with monetary outcomes. There are also many practical advantages to using money as a reinforcer. No specific deprivation procedures are required to establish money as an effective reinforcer, and monetary reinforcers are easy to manipulate and deliver. Thus, it is important to develop procedures that can produce risk proneness with monetary outcomes.

The energy-budget procedure developed in Experiment 3 was shown to be such a procedure. Unlike manipulations conducted in Experiments 1 and 2, the energy-budget manipulations produced both risk aversion and risk proneness with monetary reinforcers.

Furthermore, the shifts in risk sensitivity occurred within individual subjects and were replicated across conditions. These results have several implications for human risky choice and the cross-species generality of risky choice. Previous research has shown that choice in humans is more consistently risk averse than choice in nonhumans. The reliable patterns of risk sensitivity obtained here implies, however, that past human-nonhuman differences may have less to do with species differences than with differences in the procedures used to assess choice in humans and other animals. At least in the present case, humans' choices were shown to be similar to nonhumans' choices when behavior was studied under comparable experimental conditions.

That energy-budgets and "earnings-budgets" have similar effects on choice suggests that the patterns of risk sensitivity generated by the relationship between the gain from fixed and variable choices, current state, temporal constraints, and requirements, extend beyond those situations involving biologically important consequences. Although based upon assumptions about the fitness consequences of risk-averse and risk-prone choices for nonhuman foragers, the predictions of the energy-budget rule thus generalize to a broad range of contexts. Not only can the predictions be applied to risky choice in humans, but they can be applied to situations in which outcomes are monetary reinforcers.

Because one goal of the present research was to investigate choice in humans under conditions similar to those used with nonhumans, research and models developed by behavioral ecologists have been emphasized. The results are also relevant, however, to models developed by cognitive psychologists. Of particular note is the finding, common in judgment and decision-making research, that risky choice in humans is influenced by the probability that a choice outcome will fall above or below a particular monetary value (e.g., Payne, Laughhunn, Crum, 1980, 1981; Tversky & Kahneman, 1981). This value has been called a target, reference point, or aspiration level, and is used to explain the well-documented finding of risk aversion when choice outcomes

are gains and risk proneness when outcomes are losses (Kahneman & Tversky, 1979). Caraco and Lima (1987) have observed that the shift from risk aversion to risk proneness shown in nonhumans across positive and negative energy budgets is similar to the shift from risk aversion to risk proneness shown in humans across monetary gains and losses.

As noted by Luce (1996), however, researchers lack suitable methods for estimating targets in individual subjects. The present procedure eliminates this problem by specifically establishing targets within the experimental setting. Furthermore, because the present procedures combined the monetary outcomes typical of cognitive experiments on decision-making with energy-budget manipulations used optimal foraging research, they help establish a more direct link between models developed by psychologists and those developed by behavioral ecologists.

To date, there have been few attempts to integrate risky-choice research conducted by operant psychologists, cognitive psychologists, and behavioral ecologists into a single conceptual framework. A major obstacle to the development of an interdisciplinary approach to risky choice is the vastly different methods employed by researchers in different traditions. For example, it is unclear how models which assume that repeated choices under steady-state conditions are governed by the amount or the immediacy of a primary reinforcer can be applied to the results of studies with humans using one-shot choices and hypothetical monetary amounts. Neither is it clear how models which assume that risky choice is determined by verbally presented gambles can be applied to foraging-related choices in nonhumans. Developing a common set of procedures that can be adopted by researchers from different scientific disciplines may help promote the development of more general models and interpretations of risky choice which apply across a variety of species and choice contexts.

APPENDIX A

WITHIN-BLOCK CHOICES FOR EACH SUBJECT IN EXPERIMENT 3

Shown below are the number of fixed (F) and variable (V) choices for each trial of a block and number of accumulated points for each subject across the final three sessions of a condition (18 blocks). The total the total number of choices per trial thus equaled 18. The optimal choice for each trial and number of accumulated points is underlined. For Subject 333, only results from the final three conditions are presented.

Subject 331

	Requirement = 10 (first exposure)										Requirement = 10 (second exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	17	1									17	1								
1			0	1									0	1						
2			17	0									16	1	0	1				
3																	1	0		
4					18	0									16	0				
5															1	0			1	0
6							18	0									15	1		
7																	1	0	0	1
8									18	0									15	0
9																			1	0
10																				
11																				
12																				

Subject 331 cont.

	Requirement = 12										Requirement = 13									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	6	12									2	16								
1			1	4									0	7						
2			2	4	1	2							0	2	1	2				
3			4	3	0	4	1	0					0	9	1	0	0	1		
4					1	3	3	0							0	7	0	1		
5					0	5	1	1	1	0					0	1	2	2	0	1
6					2	0	0	7	3	0					4	2	0	1	2	1
7							2	0	5	1							0	7	3	0
8							3	0	1	0							0	4	2	2
9									0	4									1	1
10									3	0									0	3
11																			2	0
12																				

Subject 332

	Requirement = 10 (first exposure)										Requirement = 10 (second exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	17	1									15	3								
1			1	0									0	3						
2			17	0									13	2	2	0				
3					1	0									0	2				
4					17	0									12	2	0	3		
5							0	1											0	1
6							17	0									12	1		
7																	0	2	0	2
8									18	0									13	0
9																			1	0
10																			0	1
11																				
12																				

Subject 332 cont.

	Requirement = 12										Requirement = 13									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	7	11									5	$\underline{13}$								
1			1	1									0	$\underline{8}$						
2			3	$\underline{4}$	0	1							0	5	0	4				
3			6	3	0	$\underline{2}$							3	$\underline{2}$	0	2	0	3		
4					0	4	0	2							0	$\underline{4}$	0	1	0	1
5					4	$\underline{5}$	0	1	0	2					3	3	0	2		
6					$\underline{1}$	1	1	$\underline{1}$							1	$\underline{1}$	0	1	0	3
7							3	5									0	$\underline{7}$	0	2
8							$\underline{4}$	0	0	4							1	3	0	4
9							0	1	0	$\underline{4}$									0	2
10									$\underline{7}$	0									0	$\underline{5}$
11																			$\underline{1}$	0
12									0	1										

Subject 333

Points	Requirement = 10 (second exposure)										Requirement = 10 (third exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V	F	V
0	18	0									14	4								
1													0	2						
2			16	2									13	1	1	1				
3					1	0							1	1			1	0		
4					16	0									14	0	1	0		
5					0	1	0	1							2	0			0	1
6							17	0	1	0							14	0	1	0
7																	2	0		
8									16	1									14	0
9																			2	0
10																				
11																				
12																				

Subject 333 cont.

	Requirement = 13 (second exposure)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
Points	F	V	F	V	F	V	F	V	F	V
0	10	8								
1			2	3						
2			6	4						
3			2	1	3	1				
4					5	4				
5					1	3	3	1		
6					1	0	4	5	1	0
7							0	4	5	3
8							1	0	4	3
9										
10									2	0
11										
12										

APPENDIX B

GENERATING PREDICTIONS WITH A DYNAMIC OPTIMIZATION MODEL

To illustrate how the predictions of the dynamic optimization model were generated, it will be useful to work through an example similar to one provided by Houston and McNamara (1988). Consider a choice during the fifth (final) trial of a block (T-1) if 8 points have been accumulated (x=8) and the requirement was 10 points. As described in the text, the terminal fitness function, $R(x)$, was defined as:

$$R(\mathrm{x}) = \begin{cases} 0 & \text{if} \quad \mathrm{x} < \mathrm{R} \\ \mathrm{x} & \text{if} \quad \mathrm{x} \geq \mathrm{R} \end{cases}$$

Selections of the fixed option produce 2 points and selections of the variable option produce either 1 or 3 points (p=.5). If the variable option is selected, the final value of x will be either 9 or 11 with equal probability. If the fixed option is selected, the final value of x will be 10 with certainty. Thus, the expected earnings, E, at state x, given a fixed (F) or variable (V) choice, at time T-1 may be calculated as:

$E(8, \mathrm{F}, T\text{-}1) = (1 * R(10)) = (1 * 10) = 10$

$E(8, \mathrm{V}, T\text{-}1) = (.5 * R(9)) + (.5 * R(11)) = (.5 * 0) + (.5 * 11) = 5.5$

Thus, the optimal choice is the fixed option. However, if 7 points had been accumulated at *T-1* then

$$E(7, \mathrm{F}, T\text{-}1) = (1 * R(9)) = (1 * 0) = 0$$

$$E(7, \mathrm{V}, T\text{-}1) = (.5 * R(8)) + (.5 * R(10)) = (.5 * 0) + (.5 * 10) = 5$$

in which case the optimal choice is the variable option. To predict choice during the fourth trial of a block (*T-2*), the values of the terminal reward function, R(x), are replaced with the expected earnings at each state at *T-1*, designated $\psi(x)$, given that the optimal choice occurred. For example, because choice of the fixed option was optimal at x=8 and *T-1*, $\psi(8)$ at *T-2* will equal 10. Thus, if 6 points had been accumulated (x=6) at *T-2*:

$$E(6, \mathrm{F}, T\text{-}2) = (1 * \psi(8,T\text{-}1)) = (1 * 10) = 10$$

$$E(6, \mathrm{V}, T\text{-}2) = (.5 * \psi(7,T\text{-}1)) + (.5 * \psi(9,T\text{-}1)) = (.5 * 5) + (.5 * 11) = 8$$

Therefore, the optimal choice is the fixed option. At each time and state, the expected earnings are thus the average number of points that will be accumulated at the end of the block given that the optimal choice is selected on each remaining trial.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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